AD-A014 591

PRELIMINARY SAFETY ANALYSIS REPORT AND DESIGN REVIEW OF THE 2 KW(e) RADIOISOTOPE THERMOELECTRIC GENERATOR

Mueller Associates, Incorporated

Prepared for:

Naval Facilities Engineering Command

April 1975

262083

ADA014591

PRELIMINARY SAFETY ANALYSIS REPORT AND DESIGN REVIEW OF THE 2 KW(e) RADIOISOTOPE THERMOELECTRIC GENERATOR

APRIL 1975

DEPARTMENT OF THE NAVY
NAVAL FACILITIES ENGINEERING COMMAND
200 STOVALL STREET
ALEXANDRIA, VA. 22332

Preliminary Safety Analysis Report and Design Review of the 2 KW(e) Radioisotope Thermoelectric Generator

---

Mueller Associates, Inc.

MAI-127

APRIL 1975

Contract N00025-74-C-0020

Submitted to: Naval Facilities Engineering
Command, Nuclear Power Division
200 Stovall Street
Alexandria, Virginia 22332

ATTN: Code 09J

Submitted by: Mueller Associates, Inc.
1900 Sulphur Spring Road
Baltimore, Maryland 21227

FOREWORD

This document was prepared under Navy Contract N00025-74-C-0020 "Engineering Services in Connection with a Preliminary Safety Analysis and Design Review of the Navy's 2 KW(e) Radioisotope Thermoelectric Generator." The work was directed by the Naval Facilities Engineering Command - Nuclear Power Division (NAVFAC-NPD). Mr. Jerry N. Wilson was the Navy's Program Manager. Critical program reviews have been provided by Mr. Maurice Starr and Commander George Krauter of NAVFAC.

The project was conducted by Mueller Associates, Inc. (MAI), Baltimore, Maryland. Mr. Andrew J. Parker, Jr. was the Project Manager. The following members of the MAI engineering staff contributed significantly to the Program: Mr. William J. Shadis, Mr. Thomas A. King, and Mr. James S. Moore, Jr. Dr. Ralph R. Fullwood of Science Applications, Incorporated (SAI), Palo Alto, California, under subcontract to MAI, was a key contributor for safety analysis efforts. Dr. Dennis F. Hasson, a materials consultant, provided in-depth materials analysis expertise during the program.

Special thanks are due Ms. Sharon A. Lynch who typed and verified the final report.

All assessments, views, conclusions, and recommendations contained herein are those of Mueller Associates, and do not necessarily reflect the views and policies of NAVFAC-NPD.

TABLE OF CONTENTS

<u>Technical Analyses</u>

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

A Preliminary Safety Analysis Report (PSAR) and Design Review have been conducted for the 2 KW(e) Radioisotope Thermoelectric Generator (RTG). The objective of the PSAR was to appraise the risk to public health and safety resulting from the handling, transportation, emplacement, operation and recovery of the RTG system. The objective of the Design Review was to determine the state of development of the RTG system and its components and assess its ability to properly and reliably function in an undersea environment.

GLOSSARY

EOL - End of Life

BOL - Beginning of Life

GTA - Gas Tungsten Arc welding procedure

SR_2TiO_4 - Strontium ortho-titanate

(^{90}Sr) - Strontium Isotope 90

W_{th} - Watts thermal

W(e) - Watts electric

KW - Kilowatts

mW - Milliwatts

MCi - Megacuries

rem, r - Roentgen Equivalent Man

mr - millirem

TE - thermoelectric

TEM - thermoelectric module

SAE - Prefix of numerical coding sequence of the Society of Automotive Engineers for designating steel alloy constituent contents

OD - Outside Diameter

ID - Inside Diameter

ml/l - milliliters/liter

gm/cc - grams per cubic centimeter

mpy - mils per year

psig - pounds per square inch - gauge

MPCC - maximum permissible concentration

Ksi - thousand pounds per square inch

g - gram

std. - standard

in situ - in the natural or original position

preening - the act of smoothing or dressing a surface, usually with an abrasive

FY - fiscal year

IEEE - Institute of Electronic & Electrical Engineers

μ - micro

1.0 Introduction and Background

1.1 Description

A program to develop an energy conversion system utilizing a radioisotope heat source and producing 1 to 10 KW of electric power for terrestrial and undersea use was started in 1968. Designated the Isotopes Kilowatt Program, the sponsors were the Naval Facilities Engineering Command - Nuclear Power Division (NAVFAC-NPD) and the U.S. Atomic Energy Commission. A conceptual design of a 2 KW(e) Radioisotope Thermoelectric Generator (RTG) subsequently evolved. Developmental work, performed by the Naval Civil Engineering Laboratory, Naval Ship Research and Development Center, Oak Ridge National Laboratory, the 3M Company, and Westinghouse Astronuclear Laboratory, for the system components progressed to various stages of completion.

In the summer of 1974, Mueller Associates, Inc. (formerly Richard P. Mueller and Associates, Inc.) was commissioned by NAVFAC-NPD under contract number :00025-74-C-0020 to perform a preliminary safety analysis, including a design review of the 2 KW(e) RTG. Up to that time, the project work emphasized individual component development, integration and support procedures. Consequently, a systems-analysis approach design review was specified for the PSAR so that information voids and deficiencies would be identified. As stated in the Scope of Work, the preliminary safety analysis was to: "Include all design criteria and evaluate whether structures, systems, components, and their interfaces provide reasonable assurance that the unit may be handled, transported, emplaced, operated, and recovered without undue risk to the health and safety of the public."

Radioisotope Thermoelectric Generators utilize a principle of physics known since the 19th century: an electromotive force is produced in a circuit of two different conductors when a temperature difference exists between the junctions. The decay of a radioisotope which releases heat energy causes a temperature difference within the thermoelectric modules. RTG systems have been designed and manufactured to produce electric power in the unit range of microwatts to several hundred watts. They have been successfully employed in a variety of adverse environemnts including deep ocean, Arctic region, and outer space. RTG lifetime design criterion for minimum power output has typically been about 10 years. The goal of the 2 KW(e) RTG program is an RTG that will produce two kilowatts (minimum) of electric power for a 10 year lifetime, which represents a significant extension of a proven technology.

Figure 1.1 presents a system description of the 2 KW(e) RTG. Seven fuel capsules of Hastelloy C-276 containment material, each fueled with Sr_2TiO_4 will produce a total heat load of 34 KW(th). The capsules are sealed in a SAE1010 (low-carbon) steel combination heat accumulator block-radiation shield. The shield, in addition to absorbing ionizing radiation, transfers heat to twelve parallel heat pipes, also installed in the heat block-shield. The heat pipes are made from tubular stainless steel (Alloy 316) and utilize a potassium working fluid. Through the mechanism of latent heat of vaporization, potassium vapor transfers the heat energy to thermoelectric modules. One thermoelectric module is welded to the condenser end of each heat pipe. The thermoelectric modules convert the heat energy to electricity. After passing through the thermoelectric modules, the remaining waste heat is dissipated in surrounding seawater. To maximize the quantity of available heat delivered to the thermoelectric converters, the heat block is insulated. The top and bottom surfaces are covered by Kaowool fibrous insulation. Sidewalls are insulated by a fusible insulation system consisting of aluminum alloy 1100 screen, and aluminum alloy 5052 foil. During normal operation, the aluminum acts as an insulator. (Laboratory simulation of the RTG recorded heat losses of less than 10%.) Should the RTG system suffer overheat conditions that result in a temperature excursion of the heat block beyond the operating temperature range, the aluminum insulator will melt and allow heat to radiate from the side walls thus cooling the system sufficiently to prevent damage or destruction of the radioisotope containers. Finally, an envelope consisting of a pressure vessel and foundation structure provides system integrity and stability. (A more detailed description of system components is presented in Section 3.1.)

This document, presented in eight sections with appendices, summarizes the evaluation of the 2 KW(e) RTG from a systems vantage considering safety and performance aspects. Section 1 presents general RTG background information, a system description, an overview of the development of the Isotopes Kilowatt Program, and the function of this document within the program. Section 2 describes the life cycle of the RTG. Section 3, Reference Designs, defines the RTG system, environment at different phases, procedures and responsibilities. Section 4 uses the life cycle selected in Section 2 and identifies the accidents using Failure Mode and Effects Analysis (FMEA). This is the technique recommended by the IEEE for systems in the design phase. Section 5 presents a safety analysis evaluation of the RTG design. Section 6 identifies testing and development required to ensure adequacy of design and Section 7 presents recommended design modifications. Appropriate reference documents, codes, standards, etc. are included at the end of each document section.

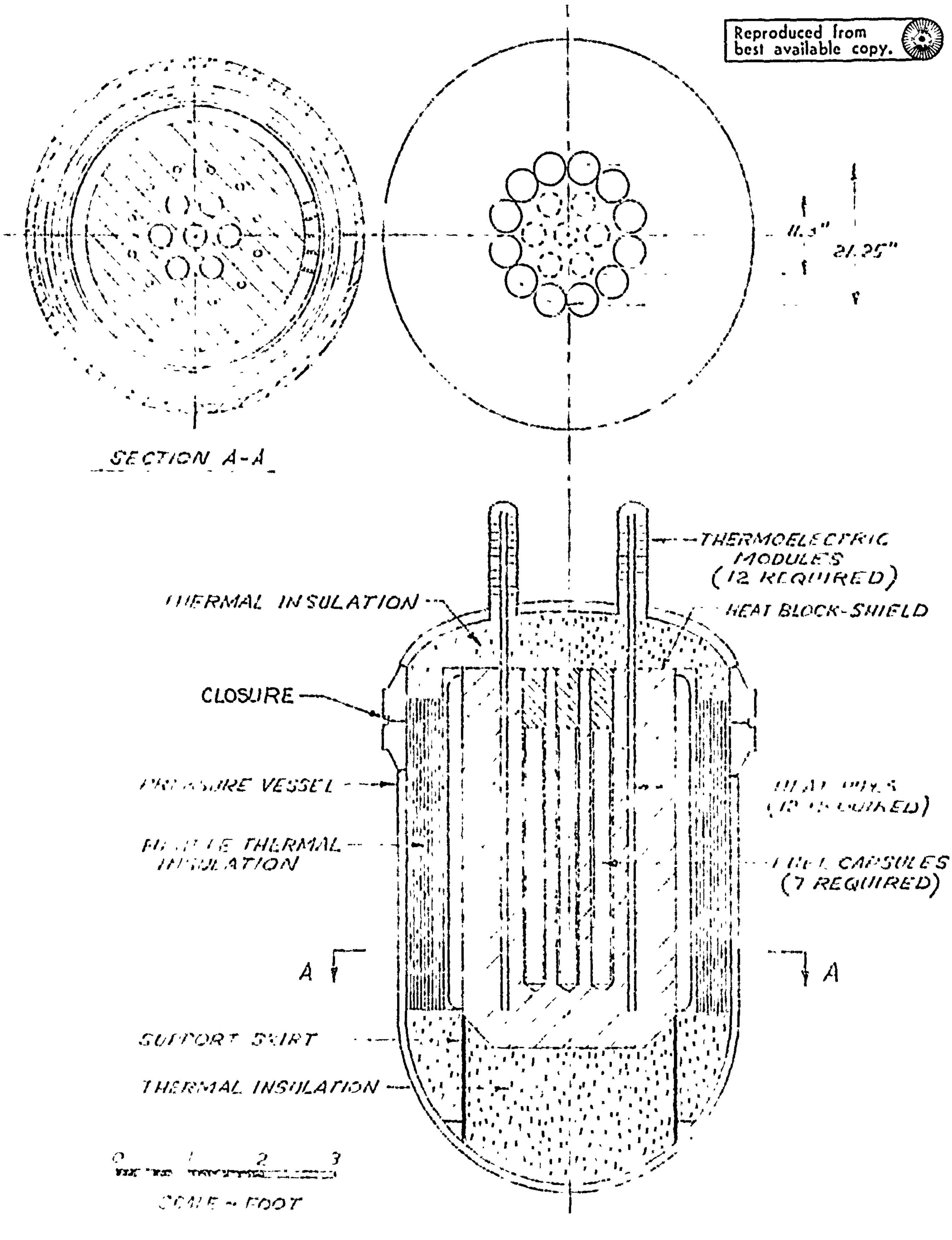


FIGURE 1.1 REFERENCE DESIGN

MAI 4/75

The last Section (8) summarizes significant data reported in the body of the report. The appendices include miscellaneous engineering analyses, evaluations of RTG component materials selections, and safety regulations applicable to radioisotopic materials and systems such as the 2 KW(e) RTG.

1.2 RTG Safety Methodology

The 2 KW(e) RTG contains 5 megacuries of strontium-90 (^{90}Sr), a known hazardous material. The design incorporates barriers to protect the public from harm or injury under all circumstances. This preliminary safety analysis is performed to determine which, if any, of the operations and accidents that may occur during the RTG life cycle could compromise these barriers. The probability of occurrence of those identified is estimated and the consequences are calculated.

The barriers protecting the environment from the isotopic fuel during normal operation are: (1) Solid, low solubility ceramic fuel in the form of SR_2TiO_4, (2) Thick (0.325 in.) fuel encapsulation of high-nickel superalloy. (3) Heat block-shield of 5.08 in. minimum barrier thickness, (4) Pressure vessel of high strength steel and (5) Site remote from human activities and food chains. To assure that these barriers maintain this integrity, engineered safety features, such as emergency cooling are provided. The design is examined and found to satisfy the single failure criterion i.e. that the failure of no single system or component can compromise the protection of the environment.

The "life cycle" of the RTG begins when the fuel (half-life 28.75 years) leaves the isotope facility. At this time, the minimum protection is the first two barriers with the other barriers being added depending upon the selected life cycle. The RTG life cycle description (Section 2.0) discusses the optional event orderings of the life cycle and the relative occurrences of each. The safety methodology of Section 4 identifies accidents using Failure Mode and Effects Analysis (FMEA). The significant accident scenarios identified by the FMEA are analyzed to assess design adequacy under normal and accident conditions. Event probability estimates are included, when available, with the possible accident consequences.

2.0 RTG Life Cycle Safety Logic Description

2.1 Life Cycle Options

The development of the RTG life cycle evolves through the occurrence of a series of events. These events include the assembly of components into an RTG system, subsequent system transportation, emplacement, and operation. Retrieval, transportation, and disassembly of the system will complete the life cycle. The ordering and occurrences of many of the life cycle events are optional. As a result, several life cycle descriptions can be hypothesized. On the following page numerous life cycle descriptions are presented. The advantages and disadvantages of each option are considered, and based on these, one option is selected as the most desirable.

The RTG includes three major subassemblies:

a) The encapsulated heat sources
b) The heat block shield
c) An assemblage consisting of the pressure vessel, heat pipes, thermoelectric modules, fusible insulation and non-fusible insulation

In order for the RTG to become functional, these subassemblies must be brought together at any one of the following locations:

1. An Isotope Facility, where the heat sources will be encapsulated
2. An Intermediate Assembly Site, having special assembly equipment, intermediate between the Isotope Facility and the Dock Facility
3. A Dock Facility, located close to dockside and equipped with the special equipment needed for the assembly of the subsystems
4. Dockside, where the RTG is loaded aboard ship

Thereafter, the assembled RTG will exist at the following:

5. Ship-Board, where the RTG is stored for transportation to the mission site
6. In transit, between the ship and the site
7. At the Seabed Site, where the RTG performs its mission
8. At the Seaburial Site, where the RTG is not retrieved (probably the same as 7)

Table 2-1 presents the numerous combinations of assembly and disassembly events possible at the different locations. The brackets identify the areas of option. For Sea Burial, there are only six options while recovery presents six options

for disassembly (primed) or 36 total combinations. Figure 2.1 is a schematic presentation of these combinations.

TABLE 2-1 - Possible Options in the RTG Life Cycle

(a) Combinations Resulting in Sea Burial

$$\left.\begin{matrix} a\ b\ 1\ c\ 1 \\ a\ b\ 1\ c\ 2 \\ a\ b\ 1\ c\ 3 \\ a\ b\ 2\ c\ 2 \\ a\ b\ 2\ c\ 3 \\ a\ b\ 3\ c\ 3 \end{matrix}\right\} 4,5,6,7,8$$

(b) Combinations Resulting in Retrieval

$$\left.\begin{matrix} a\ b\ 1\ c\ 1 \\ a\ b\ 1\ c\ 2 \\ a\ b\ 1\ c\ 3 \\ a\ b\ 2\ c\ 2 \\ a\ b\ 2\ c\ 3 \\ a\ b\ 3\ c\ 3 \end{matrix}\right\} 4,5,6,7,6',5',4' \left\{\begin{matrix} c\ 1'\ a\ b\ 1' \\ c\ 2'\ a\ b\ 1' \\ c\ 3'\ a\ b\ 1' \\ c\ 2'\ a\ b\ 2' \\ c\ 3'\ a\ b\ 2' \\ c\ 3'\ a\ b\ 3' \end{matrix}\right.$$

2.2 Discussion of Possible Options

2.2.1 Assembly

2.2.1.1 Assembly of Sources and Heat Block Shield at (a b 1) the Isotopes Facility

The Isotopes Facility is suitable for assembling the heat sources into the heat block shield because of the availability of remote handling equipment for radiological and thermal protection.

Once the sources and shield have been assembled, the local radiation levels are reduced substantially to permit personnel to work nearby with the RTG unshielded. The large mass of this assembly also provides thermal inertia and convective cooling that facilitates handling. The shield block surface temperature will be about 480°F.

The heat block shield provides the rugged packaging necessary for a type "B" container as specified by the Nuclear Regulatory Commission (NRC-formerly AEC) and DOT requirements for commercial transportation. The only item of these requirements (Appendix F) that is not satisfied is the maximum contact surface temperature limit of 180°F.

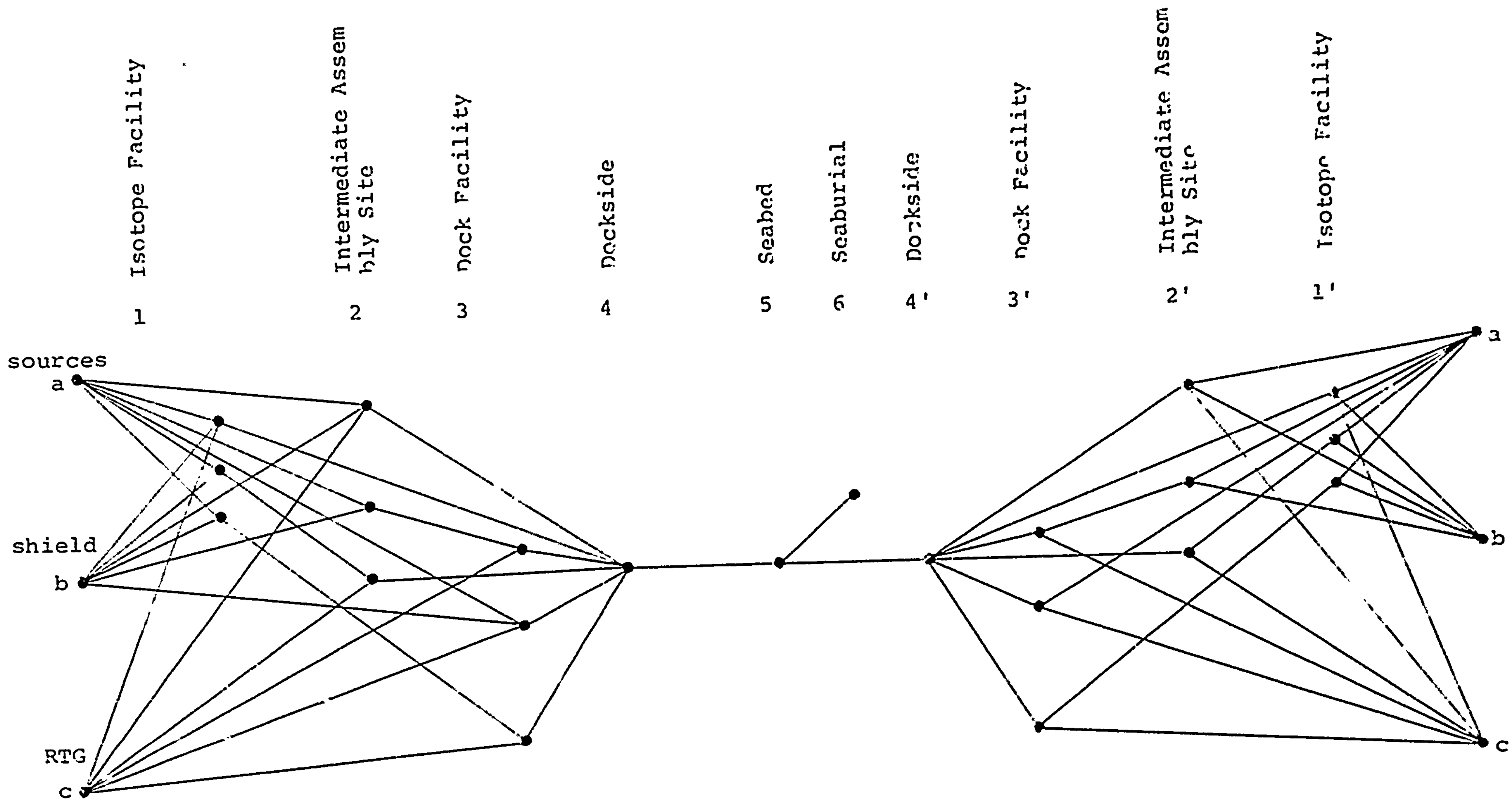


FIGURE 2.1

RTG Life Cycle Schematic With Options

The incorporation of the sources and heat block-shield at this point in the life cycle is highly desirable. The resulting package is suitable for handling and transportation without other hardware.

2.2.1.2 Full Assembly at the Isotopes Facility (a b 1 c 1)

This is a satisfactory option and depends primarily on contract agreements. The shipping weight of the assembled RTG is increased somewhat over the fueled shield block alone but not excessively for either special truck or rail transport. Normal vibration of the shipment could have adverse effects. Provision for emergency cooling in the event of heat pipe failure must be included.

A method must be devised to remove waste heat from the RTG thermoelectric modules to keep the components at or below normal working temperatures.

2.2.1.3 Source-Shield and RTG Assembly at An Intermediate Assembly Site (a b 1 c 2)

This option combines the problem of shipping the source-shield assembly with its high contact temperature and the problem of cooling the RTG, once assembled. Neither problem if overly difficult. The advantage of the Intermediate Assembly Site is that it could have equipment for test and assembly not present at either the Dock Facility or the Isotopes Facility. This could be the location of the prime contractor wherein are located equipment and procedures required for assuring quality control and guaranteeing performance.

2.2.1.4 Source-Shield and RTG Assembly at the Dock Facility (Reference Design) (a b 1 c 3)

This option takes advantage of the rugged heat block shield as a transportation container for the heat sources and minimizes the amount of continental transportation of the assembled RTG. It still requires a solution to reduce the contact temperature problem to the DOT/NRC specification of 180°F and it also requires a solution to the problem of maintaining the RTG temperature to operational bounds when in surface shipment. The principal constraint on this option is the capability of the Dock Facility in terms of equipment and procedures to perform the necessary assembly and tests.

2.2.1.5 Full Assembly at the Intermediate Assembly Site (a b 2 c 2)

This option requires continental transport of the heat source without benefit of the heat block shield acting as the shipping container. This could be done using a commercial spent reactor fuel cask but requires the special remote handling equipment discussed under a b 1. This option seems to offer no advantages.

2.2.1.6 Partial Assembly at the Intermediate Assembly Site - Complete Assembly at Dockside (a b 2 c 3)

This option combines the disadvantages of shipping the heat sources without the heat block shield and continental transport of the assembled RTG. It requires remote handling facilities at the Intermediate Assembly Site and test and assembly equipment at the Dock Facility.

2.2.1.7 Full Assembly at the Dock Facility (a b 3 c 3)

In this option, the sources would be shipped in cooled shielded casks. Commercial spent fuel casks already licensed for this purpose could be used. The satisfaction of some regulatory requirements would be facilitated. The Dock Facility would need all the special handling, assembly and test equipment mentioned earlier.

2.2.3 Transportation to Dockside (4)

Regardless of where assembly is completed, the normal mode of transportation to dockside would be by a wheeled carrier. A mobile heat removal system capable of maintaining an acceptable thermoelectric module temperature would be required.

2.2.4 Transportation to the Mission Site (5)

The RTG will be loaded onto the ocean transport vessel by crane and secured for the ocean voyage. The RTG, may be secured to its foundation at the dock or on arrival at the mission site. The heat removal systems used to protect the TEM must continue to operate at all times. Personnel protection from all hot exposed RTG surfaces must be provided.

2.2.5 Emplacement (6)

After arrival at the mission site, the RTG/Seabed foundation and mission package will be lowered over the side of the vessel by cable and winch. Upon entering the water, the auxilliary heat removal system used to protect the TEM's during surface transport must be removed. The surrounding seawater will provide cooling thereafter.

The most credible accident possible during shipboard handling and emplacement is cable breakage or winch brake failure. In either case, the RTG will either fall onto the ship or into the water.

2.2.6 Operation at the Mission Site (7)

During operation of the RTG, failures that could have safety implications require failures of the barriers as described in Section 1.2.

2.2.7 Seaburial (8)

Should the RTG be lost or difficult to recover and it is deemed that its non-recovery is acceptable, the option of seaburial may be exercised. The accident and failure modes for this option are no different from normal operation up to the point of recovery. Seaburial means that the RTG barriers will be subject to the site environment forever.

2.2.8 RTG Recovery from the Mission Site (6')

The recovery of the RTG will probably be made by some form of grappling. The RTG foundation mounting will be designed to release the RTG so that the foundation (which will probably be imbedded in the ocean bottom) can remain behind and only the RTG be recovered. Recovery of the RTG poses no unusual safety problems not associated with recovery of a similar weight and size device. If the cable or grapples should break after the RTG is removed from its foundation, the RTG may become misoriented and imbedded in the Seabed. Location and recovery after such an incident will be extremely difficult.

If the RTG has failed during its mission, it is possible that the failure may be due to the presence of a small seawater leak. When the RTG is brought to the surface, the pressure vessel may be pressurized up to 10,000 psia which can constitute a personnel safety hazard if pressure equilibrium cannot be maintained. Some safe means to achieve pressure equilibrium is needed.

Standard radiological surveys of the RTG should be performed to determine if radioisotope leaks are present.

2.2.9 Ocean Transport to Dock (5')

Once the RTG is successfully removed from the ocean, the surface transporation heat removal system must be reinstalled. At the end of the specified 10 year mission, the RTG heat flux is still 79% of the original value and hence the RTG must be handled in about the same manner as during emplacement.

One possible option not shown in Figure 2.1 or Table 2.1 is that the RTG may be recovered for a new mission assignment at a different location before the ten year lifetime is completed. The vessel may go directly to the new site and emplace the RTG without returning to dockside. This poses no additional safety problems other than those considered during the original emplacement.

2.2.10 Transportation From Dockside (4') and Disassembly

If the RTG is returned for repair or salvage, it will be returned to a dock and be off-loaded onto a wheeled vehicle for transport to a location nearby for disassembly. No additional safety problems are posed other than those that occur in the original one-emplacement trip. As before, an auxilliary heat transfer system must continue to operate if it is desirable to protect the TEM's. If the RTG is allowed to overheat, the fusible insulation will melt and the RTG will cool to a surface temperature of about 400°F. It is not possible to transport any device at that temperature by commercial carrier. Disassembly is simply a reversal of the assembly process by one of the six options discussed earlier. The same considerations as to safety and handling apply.

2.3 Summary and Selected Option

The meaningful options available for RTG transportation and assembly have been discussed. Advantages and disadvantages for each option have been presented. At this time, no specific assembly and transport procedure has been expressed in the Reference Documents. Obviously, all of these possible combinations cannot be discussed in the detail required for safety analysis and henceforth only a selected procedure will be used. The selected procedure is composed of options a b 1 c 3, that is, the sources are installed in the heat block-shield at the isotope facility. This unit is then transported by commercial surface transportation to a Dock Facility and assembled into the RTG subassembly. It is subjected to various tests to assure its performance; sealed, retested and loaded aboard ship to execute its mission. It is recovered and disassembled by a reversal of the assembly process thus completing the life cycle (a b 1 c 3 4 5 6 7 6' 5' 4' c 3' a b 1') which is reviewed in-depth under this contract.

3.0 Reference Designs

3.1 Radioisotope Thermoelectric Generator

The 2KW (e) RTG (shown in Fig. 3.1) is essentially a system of three subassemblies comprising six major components: fuel capsules, a combination heat block-biological radiation shield, heat pipes, thermoelectric modules, fusible thermal insulation, and an enclosure vessel. A discussion of the function and design status of each component follows:

3.1.1 Fuel Capsule

Seven fuel capsules of Hastelloy C-276 alloy, each containing the radioisotope ^{90}Sr in the form of Sr_2TiO_4, will provide approximately 34 KW (BOL) of thermal energy (4860 watts per capsule). Capsule exterior dimensions are 102.3 cm (40.28" long by 10.4 cm (4.1") diameter. The capsules will be fabricated into a hollow cylinder from bar stock. Top and bottom end caps will be fabricated for electron beam welding to the cylinder (Fig. 3.2).

For each capsule, 24.95 kg (55 lbs.) of Sr_2TiO_4 is to be placed in liners of Hastelloy C-276. Liners will be sealed by Gas Tungsten Arc (GTA) or plasma arc welding, leak tested and decontaminated prior to insertion into the capsule. Design details of the liners are not available. This assembly is loaded into the capsule housing. The fuel capsule fabrication and performance design criteria are listed in Table 3-1. Comparisons of Hastelloy, Inconel-625 and other materials for this application are presented in Appendix C.

3.1.2 Heat Block-Biological Radiation Shield

The fuel capsules are installed in the heat block radiation shield (Fig. 3.3). As the name implies, this component serves a dual purpose; the transfer of heat energy and the absorption of ionizing radiation. In the current design the block is a finned cylinder of SAE 1010 steel though an alternative material, Nickel Alloy 201, has been considered. (A further discussion of these alternatives is presented in Appendix B). The fuel capsules are to be installed in a hexagonal array on an 11.3 in. diameter circle with the seventh capsule located at the heat block center. The heat block-radiation shield accomodates 12 heat pipes (See Section 3.1.3). These are arranged symmetrically on a 21.5" circle. Heat block information is summarized in Table 3-2.

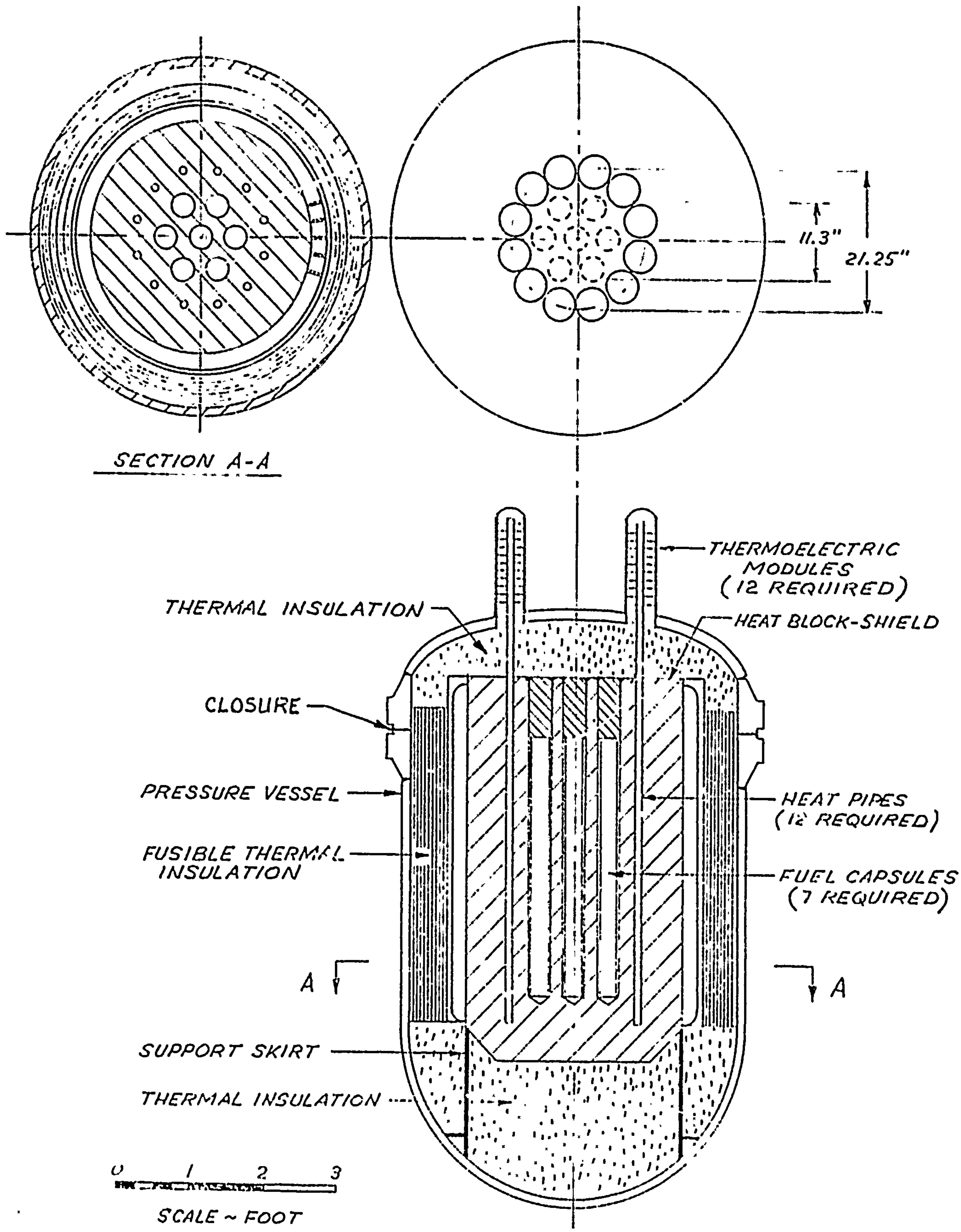
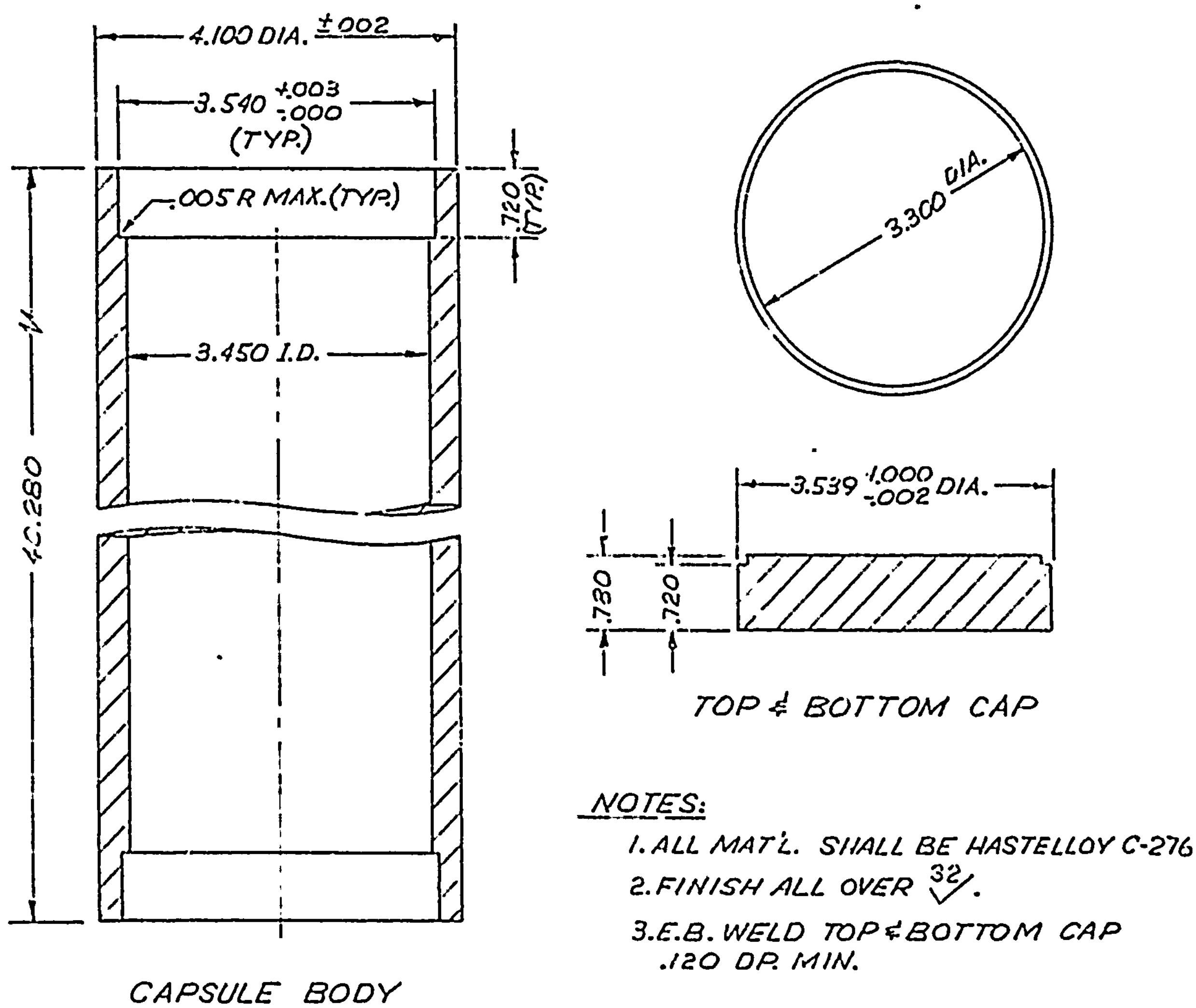


FIGURE 3.1 REFERENCE DESIGN

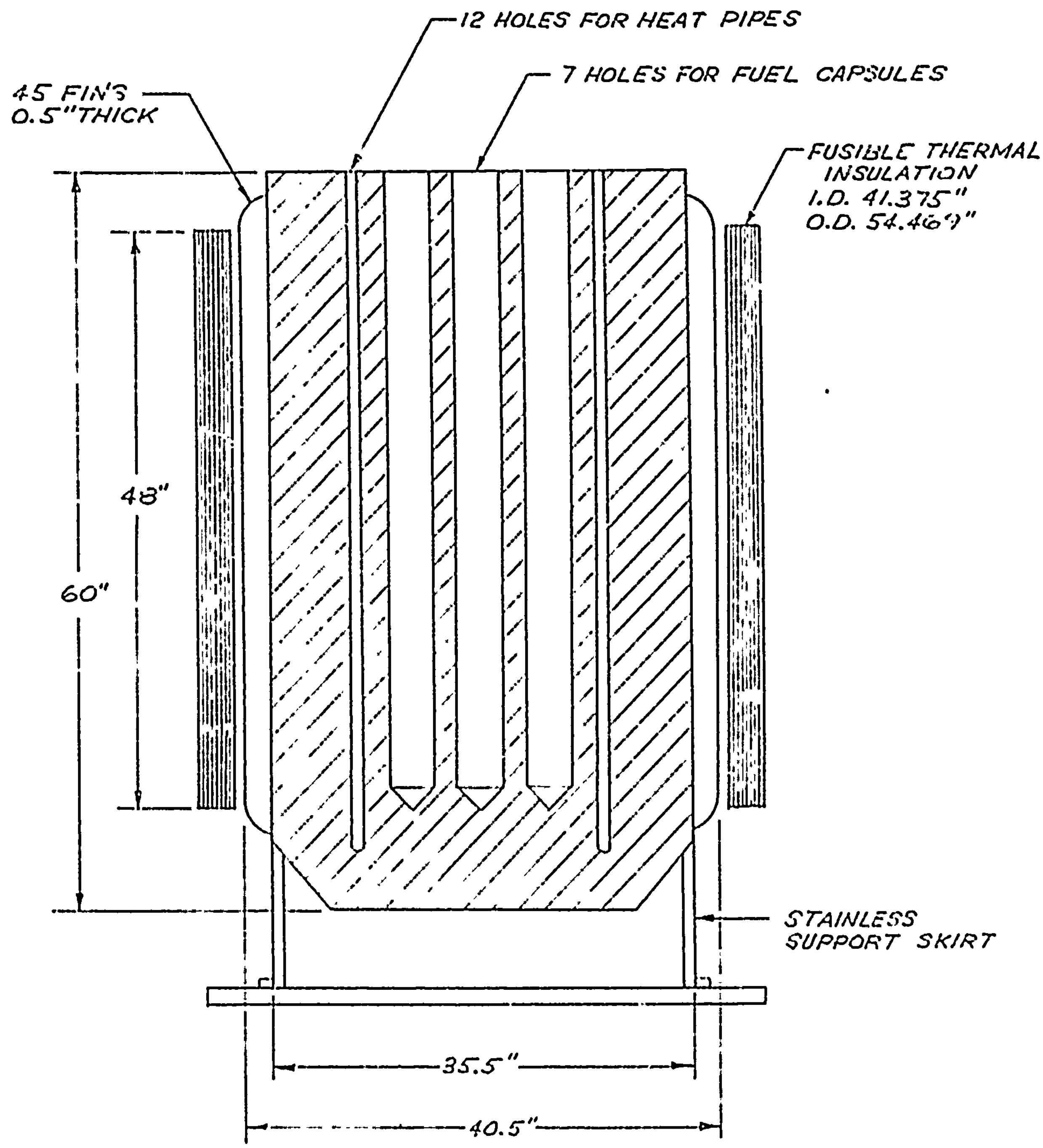
MAI 4/75



ISOTOPE KILOWATT PROGRAM FUEL CAPSULE

FIGURE 3.2

MAI 4/75



HEAT BLOCK - SHIELD
FUSIBLE INSULATION

FIGURE 3.3

MAI 4/75

TABLE 3-1

SUMMARY OF FUEL CAPSULE INFORMATION

Fuel Capsule Parameter	Specifications
Quantity	7
Fuel:	Sr_2TiO_4 (^{90}Sr)
Fuel Half Life (years):	28.75
Fuel Weight (Approximate kg per capsule)	24.95 (55 lbs)
Fuel Power Capacity (Per capsule-W_{th}):BOL	4860
EOL	3820
Housing Material:	Hastelloy C-276
Normal Operating Temperature (^oF)	
Fuel:	1900
Housing Surface:	1360
Welds: Top	E.B. - .120" DP. Min.
Bottom	E.B. - .120" DP. Min.
Sr_2TiO_4 Form:	Cylindrical Pellets
Pellet Dimensions: (Inches)	
Length:	1.92
Diameter	3.4
Pellet Quantity (Per Capsule):	20
Maximum Temperatures Accident(Loss Of Coolant) Operating Temperature* (^oF)	
Fuel:	2400
Housing Surface:	1890
Shipping Temperature* (^oF)	
Fuel:	1580
Housing Surface	1020
Shipping Accident Temperature* (^oF)	
60^o Burial:	1165
110^o Burial:	1190

* Temperature is maximum for test

TABLE 3-1 (continued)

SUMMARY OF FUEL CAPSULE INFORMATION

Fuel Capsule Parameter	Specifications
Hastelloy C-276 Seawater Corrosion Rate (in./yr.):	10^{-4}
Design Life (Years):	10
Maximum Pressure:	15,000 psia
Vibration: Frequency (CPS)	5 - 5000
Force Loading (G)	Unknown
Thermal Shock:	1400°F to 32°F
Impact:	Capsule Free Fall from 30'
Puncture:	7 KG mass dropped from height of 1 Meter
Thermal:	2000°F for 30 min.
Immersion: (Water)	2' above capsule for 24 hours
Housing Dimensions: (See Fig. 3.1)	
Outside Diameter, in.	4.100 (± .002)
Inside Diameter, in.	3.450
Length, in.	40.280

TABLE 3-

SPECIFICATIONS, DESIGN AND PERFORMANCE DATA
FOR THE HEAT BLOCK-SHIELD

Material	SAE 1010 Steel
Diameter	
Fin root, in.	35.5
Fin tip, in.	40.5
Height, in.	60
Number of fins	45
Fin height, in.	2.5
Fin thickness, in.	0.5
Holes for heat pipes	
Number	12
Diameter, in	1.008
Length, in.	55
Centerline circle, in.	21.25
Heat block-shield assembly shipping weight without fuel capsules, lb.	16,500
Radiation Dose at Surface (mr/hr)	<200
Normal Operating Temperature (°F)	1150
Accident Condition Operating Temperature (°F)	1360
Shipping Temperature (°F)	480
Power Loss KW (th) During Normal Operations	5.8 (1100°F - Surf. Temp. 1.0 psia)
Shipping Accident	
60° Burial: in Sand (°F)	770
out of sand (°F)	600
110° Burial: in Sand (°F)	825
out of Sand (°F)	635

3.1.3 Heat Pipes

A program of heat pipe development and testing was conducted in an effort to improve operational performance and increase confidence in component reliability. The present design, in addition to being fabricated to dimensional specifications, was required to meet the following operational specifications:

1. The heat pipe shall be capable of delivering a minimum of 3500 watts to its condenser section at 900°F for a minimum of 10,000 hours.

2. The heat pipe shall be capable of operating in the temperature range 900°F to 1100°F for a minimum of 10,000 hours.

3. The heat pipe shall be capable of being started from room temperature by vertical insertion into a 1000°F heat block.

4. The heat pipe assembly shall be capable of operation in attitudes ranging from vertical to 60° below vertical.

5. The heat pipes shall use potassium as the working fluid. (See Section 6 for further discussion on the selection of working fluid).

Figure 3.4 presents a sketch of heat pipe elements. Additional design criteria are listed in Table 3-3.

3.1.4 Thermoelectric Modules

The design for the Thermoelectric Modules (TEM's) is shown in Fig. 3.5. Design details are shown in Fig. 3.6. Principle components of the TEM are two piece conductor rings, a duplex inner clad, and glass seals, located at nickel power pin penetration points. The tubular, layered, design maximizes the component reliability while minimizing temperature drops between the circuit and both the hot and cold reservoirs.

Design and performance criteria for the modules are presented in Table 3-4. These criteria were developed for a five year system life. A recent upgrading of the RTG design life to ten years requires that the existing TEM design be optimized for ten year performance. This will be done within the framework of the current TEM conceptual design, i.e. dimensions and materials will change; but not the configuration.

TABLE 3-3

HEAT PIPE DESIGN DATA

OD	1"
ID	.834"
Length	79"
Working Fluid	Potassium
Charge (fluid mass)	Unspecified
Wick Material	Type 316 Stainless Steel
Type of Wick Structure	Wrapped Screen
Pipe Wall Material	Type 316 Stainless Steel
Operating Temperature Range	900^{o}F to 1100^{o}F
Thermoelectric Module Power Requirement (Each)	2.7 KW (th)
Heat Pipe Power Capacity (Each @900^{o}F)	35 KW (th)

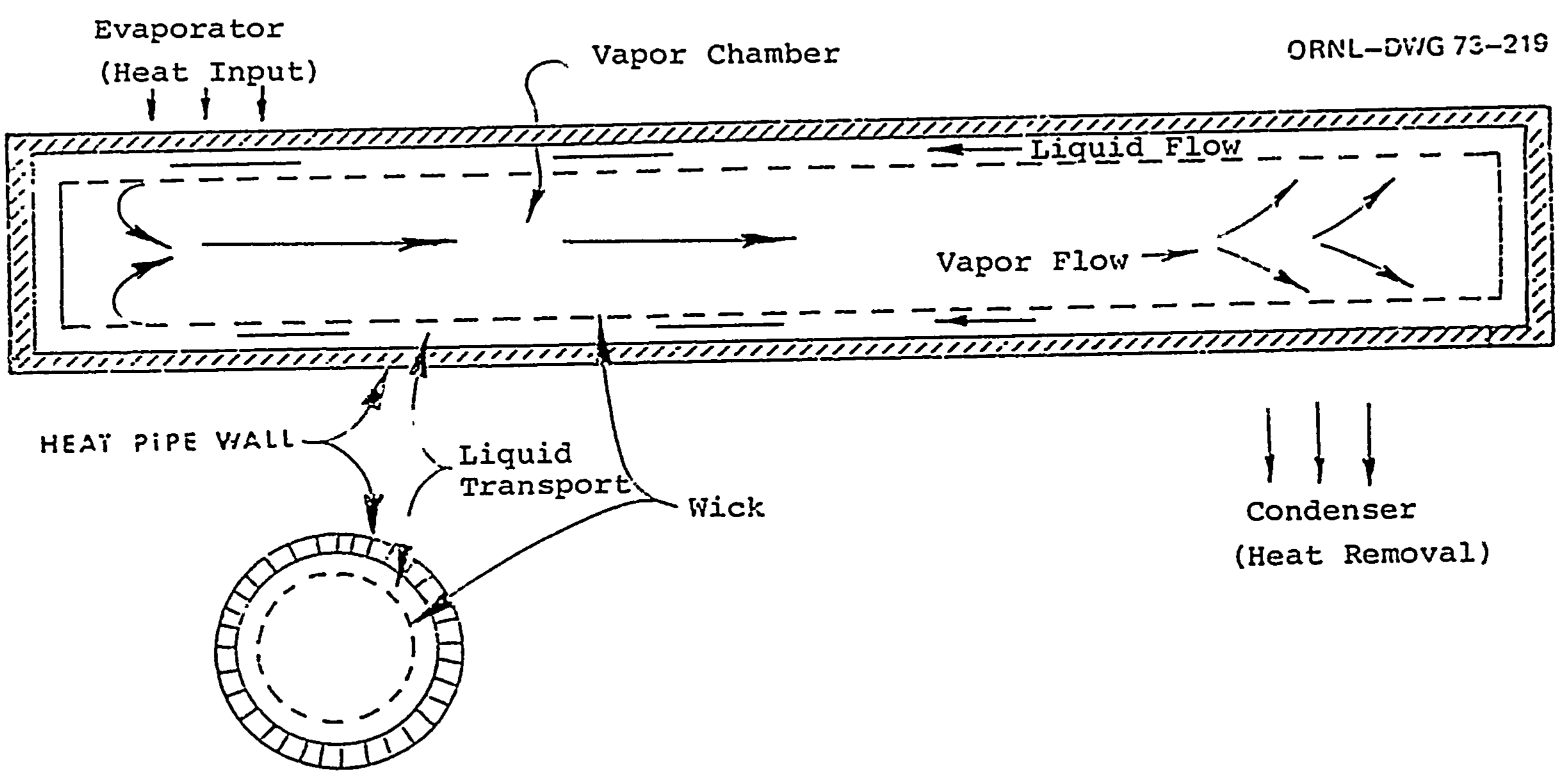
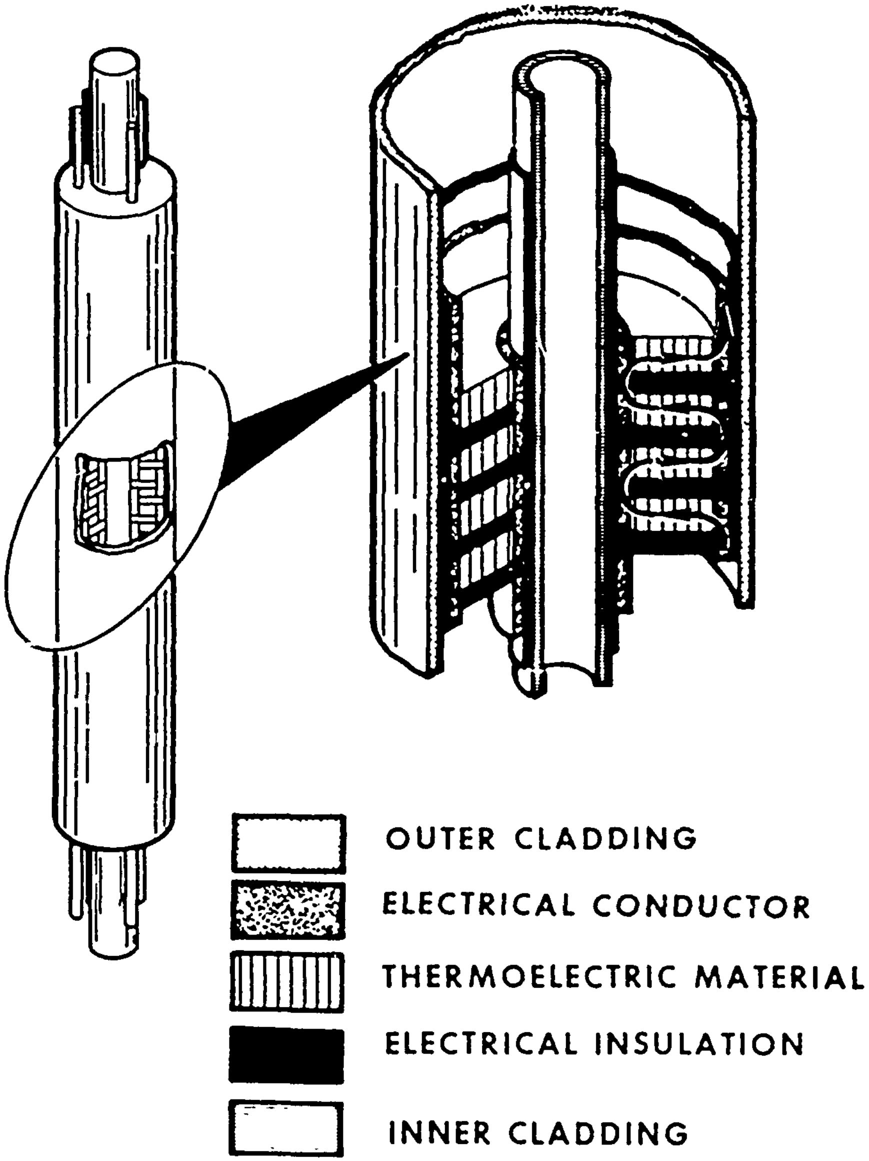


Fig. 3.4 Heat pipe structure.



DESIGN FEATURES

- FULLY ENCAPSULATED
- FULLY COMPACTED-VOID FREE
- STRUCTURALLY RUGGED
- NO BONDED JOINTS
- USES PbTe AT HIGH TEMPERATURE
- MECHANICALLY AND ELECTRICALLY ADAPTABLE
- LONGEVITY- SHELF AND OPERATING

Astronuclear Laboratory

Figure 3.5 Tubular Thermoelectric Module

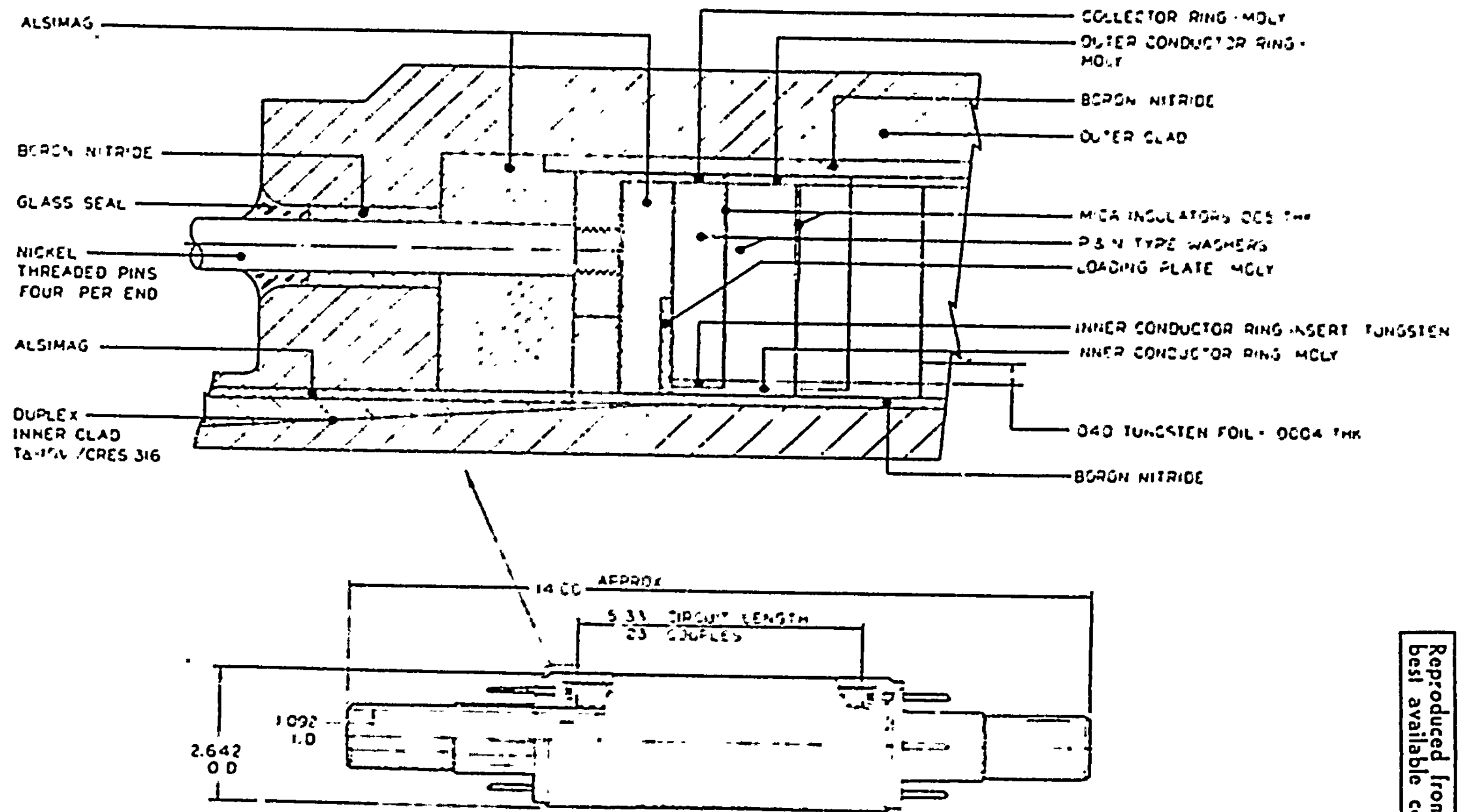


Figure 3.6 Reference Module TEM-17 Schematic

31

TABLE 3-4

TEM-17 REFERENCE MODULE SUMMARY

DESIGN DATA

Inner Diameter (inch)	1.092
Outer Diameter (inch)	2.642
Circuit Length (inch)	5.33
N-Leg Washer Thickness (inch)	0.130
P-Leg Washer Thickness (inch)	0.093
Tungsten Foil Axial Thickness (inch)	0.0004
Tungsten Foil Radial Thickness (inch)	0.040
Number of Couples	23

CALCULATED PERFORMANCE DATE

	B.O.L.	E.O.L. FUEL DECAY	E.O.L. CONST $\overline{T}_H$
Heat Input (watts)	2600	2200	2560
$\overline{T}_H$ (^oF)	1000	872	1000
$\overline{T}_C$ (^oF)	75	75	75
Load Voltage (volts)	2.2	2.2	2.2
Efficiency (percent)	7.7	6.7	7.3
Power Output (watts)	200	148	189
Power Degradation (pct/10,000 hrs)			
Module Induced	-	1.3	1.3
Fuel Induced	-	4.6	0.
Total	-	5.9	1.3

3.1.5 Fusible Thermal Insulation

Insulation around the heat block is required in order to minimize parasitic heat losses. However, in the event of coolant system (heat pipe) failure, it will be necessary to reject heat by another method in order to avoid damaging or destroying the integrity of the fuel capsules. This dichotomy is satisfied by 6 1/2 inches of aluminum foil and screen insulation (see Fig. 3.7) which consists of 8 layers of foil to every layer of screen. Support for the insulation system is provided by a frame that consists of inner and outer frames of expanded steel. These alloys melt in the temperature range of 1125°F to 1215°F, and thus allow the heat block and fuel capsules to reject heat through the previously insulated sides of the RTG. Specifications for the insulation, including properties of the aluminum alloys employed follow in Tables 3-5 and 3-6.

3.1.6 Pressure Vessel

The RTG is intended for operation at maximum design seawater depth of 20,000 feet. To accomplish this, the system will be enclosed in a high strength pressure vessel (See Fig. 3.8). The vessel will be a cylinder with external ring stiffeners. To minimize bending stresses, the top end cover will be torispherical, (a spherical cap segment at apex, blending into a toroidal section) and the bottom end cover will be hemispherical. Twelve thimble-like protrusions will be required on the top cover to accomodate the thermoelectric module units. The pressure hull material will by HY-100 steel. A bolted closure joint will be required. (A discussion of closure alternatives is presented in Appendix A.) Design data for the pressure hull is given in Table 3-7.

3.2 Ocean System

The RTG must be exposed to free moving water and held in a near vertical attitude on the sea bed. The RTG configuration and weight are such that a large foundation is needed for these purposes. The system will provide electric power to a nearby experiment or mission package via submarine cables. This entire assembly, consisting of the RTG, electrical penetrator, support foundation and mission package is called the "Ocean System."

3.2.1 Foundation

The Foundation affords the generator (especially the thermoelectric modules) protection from the effects of ocean currents, earthquake activity, animal and plant life, and the slope of the

TABLE 3-5

CHEMICAL COMPOSITION AND MELTING RANGE OF THE FUSIBLE INSULATION WIRE AND FOIL

Element	Alloy 1100 (Screen)	Alloy 5052 (Foil)
Silicon plus iron (max), %	1.0	0.45
Copper (max), %	0.20	0.10
Manganese (max), %	0.05	0.10
Magnesium, %		2.2 - 2.8
Chromium, %		0.15 - 0.35
Zinc (max), %	0.10	0.10
Other Elements		
Each, %	0.05	0.05
Total, %	0.15	0.15
Aluminum (min), %	99.00	Remainder
Melting Range, deg. F	1190-1215	1125-1200

TABLE 3-6

DIMENSIONS OF THE FUSIBLE INSULATION FOR HEAT-BLOCK

Expanded Metal Liners	
Type Flattened Expanded Metal	1½ in. No. 16-18
Nominal thickness, in.	0.047
Width, in.	48
Material	Stainless steel
Inside diameter	
Inner liner, in.	41.375
Outer liner, in.	54.469
Number of Foil Layers	38
Number of Screen Layers	301
Total Insulation Thickness, in.	6.5
Average Screen Layer Thickness, in.	0.021

PHOTO 6143-73

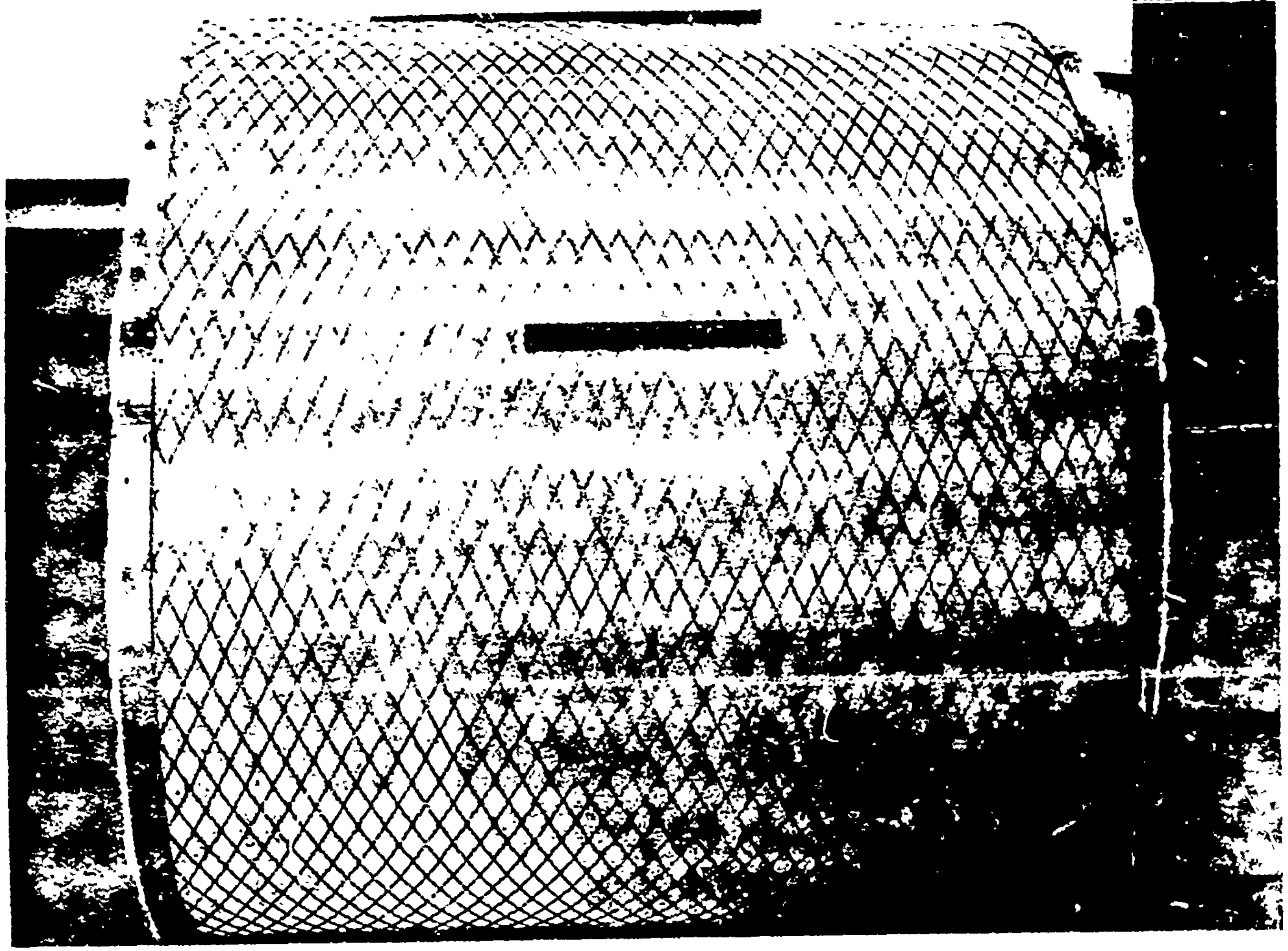


Fig. 3.7 Completed flexible insulation with the outer layer of expanded metal installed.

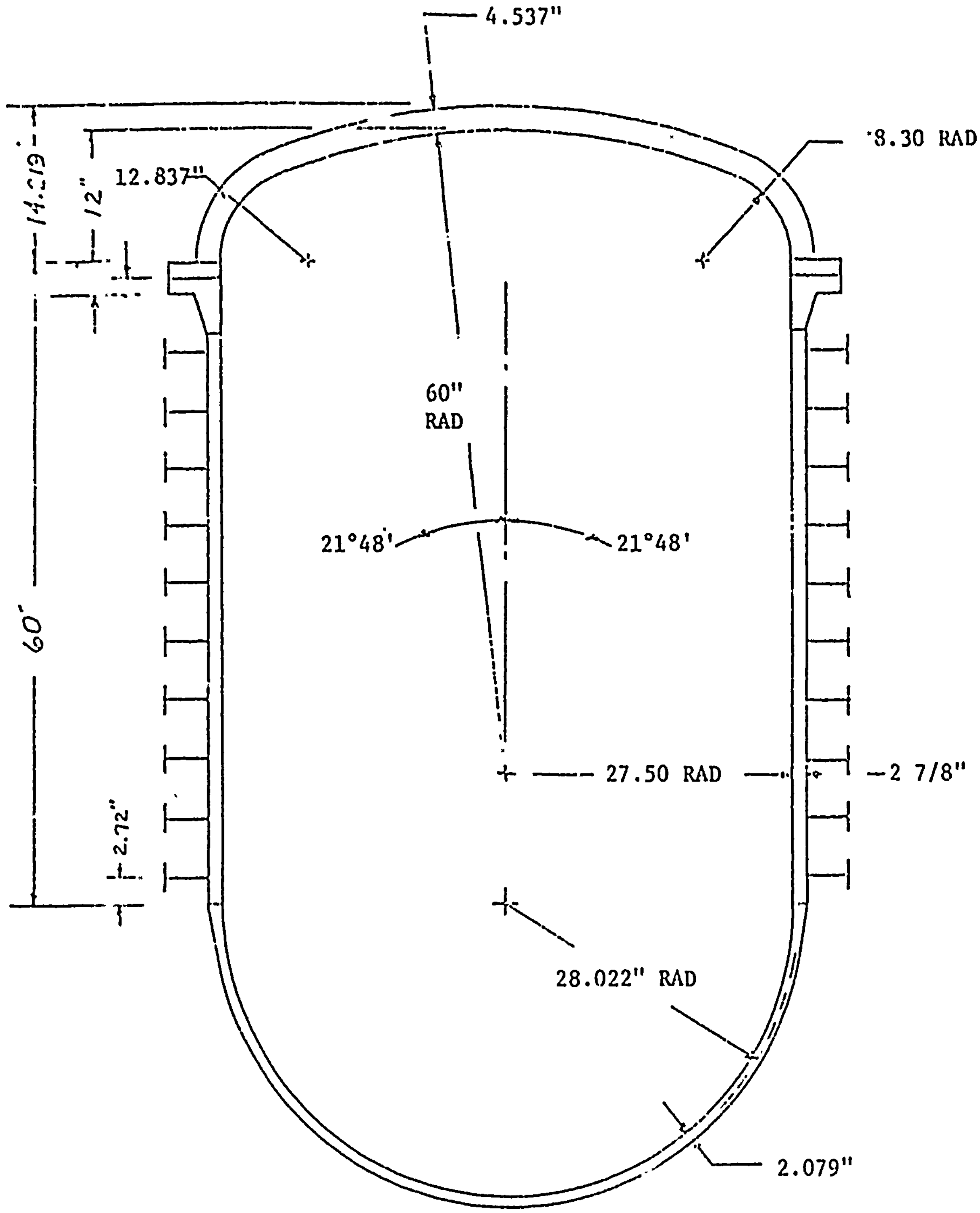
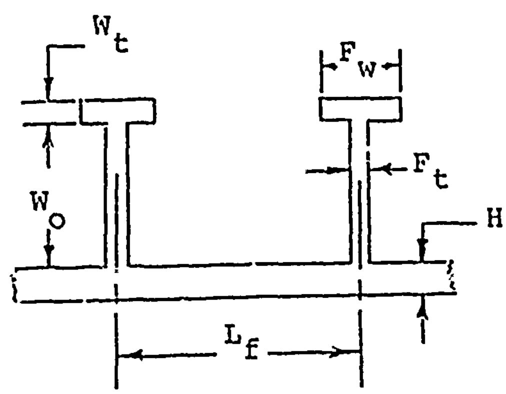


Figure 3.8
HULL CONFIGURATION - HY-100 - STEEL (20,000' APPLICATION)

TABLE 3-7

PRESSURE VESSEL SPECIFICATIONS

Detail of Ring Stiffeners



Hull and Stiffener Material: HY-100 Steel

Hull Surface Finish: 63 RMS

"O" Ring Material: BUNA-N

Design Depth: 20,000'

Cylindrical Section: Length: 60.0"
Shell Radius: 27.5"
Out-of-Roundness Tolerance: .125"

Submerged RTG Weight: 21,520 lbs.
Submerged Foundation Weight: 2,680 lbs.
Total System Weight: 24,200 lbs.

Detail of Ring Stiffeners:

H:	2.250"	W_t:	.24"
L_f:	5.45"	F_w:	2.43"
W_o:	4.05"	F_t:	0.61"

Frame to Shell Area Ratio: 0.2

Weight to Displacement Ratio: 1.377

Internal Operating Pressure: 16 psia

Internal Gas: Argon

ocean floor. The Foundation also facilitates installation and retrieval, as well as offers security from other damage (either malicious or unintentional) by man. It also maintains the RTG in an attitude that will allow the heat pipes to function at maximum efficiency. The design for the support and foundation structures is shown in Figures 3.9, 3.10, and 3.11. This design includes the use of magnesium bolts to secure the foundation to the support elements. It is intended that these bolts will corrode in a few days, thus allowing the recovery of the RTG without the added weight of the foundation. The figures present only a conceptual design. No considerations of corrosion effects are given. Contrary to the pressure vessel reference design, no external stiffening rings are assumed. Incorporating the stiffening rings into the pressure vessel/ support structure is required and may require modifications to the conceptual foundation design.

3.2.2 Electrical Penetrator

A design for an electrical penetrator has been recommended. This design, shown in Fig. 3.12, was prepared for the U.S. Navy for use in depths of 0 to 20,000 feet. Both plug and receptacle have compression glass sealed and insulated pin contacts designed for pressures experienced at 20,000 feet. Redundant "O-ring" seals are also featured. The penetrator housing material is Inconel-625. Though the figure shows a 90 degree plug, a straight penetrator can also be used.

3.2.3 Mission Experiment or Package

There are presently no reference designs or specifications relating to the types of missions for which the 2 KW (e) RTG might be used. However, it is assumed that any such mission will be located near the RTG and connected to it by a submarine transmission cable.

3.3 Emplacement Maintenance and Retrieval Systems

Emplacement and retrieval systems for the 2KW (3) RTG have been discussed in reference to an undefined mission that may require covertness. Covertness, defined as concealing what is being done rather than where it is being done, would require a ship that is as small as possible or a ship that would not reveal the intent of the mission. The USNS HAYES (T-AGOR-16), with a proposed 25 ton crane, was suggested as a satisfactory choice for a deepwater installation vessel. A maximum sea state of 3 has been specified for emplacement or retrieval. Installation of the RTG will be accomplished in the following way:

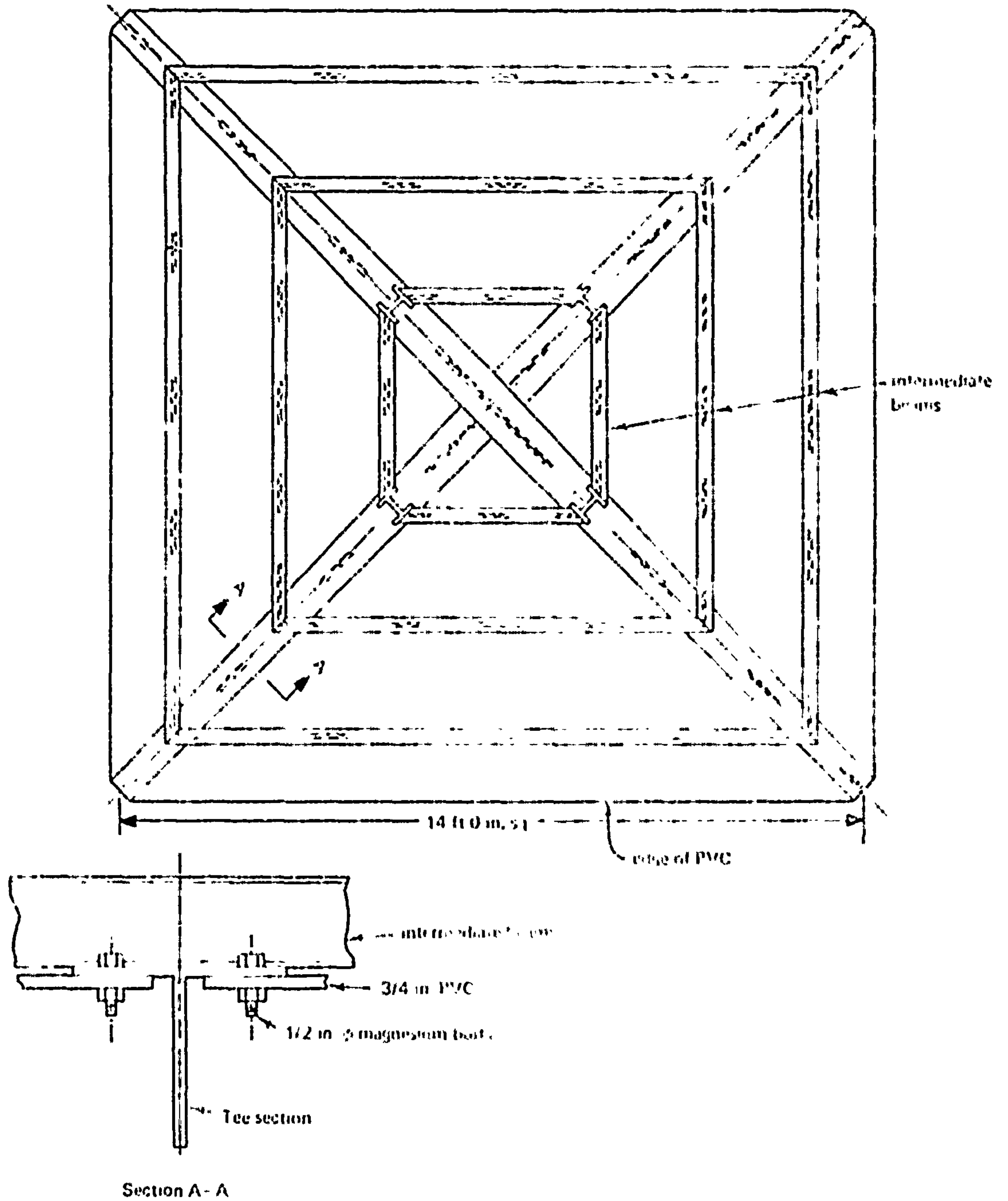


Figure 3.9 Possible foundation configuration.

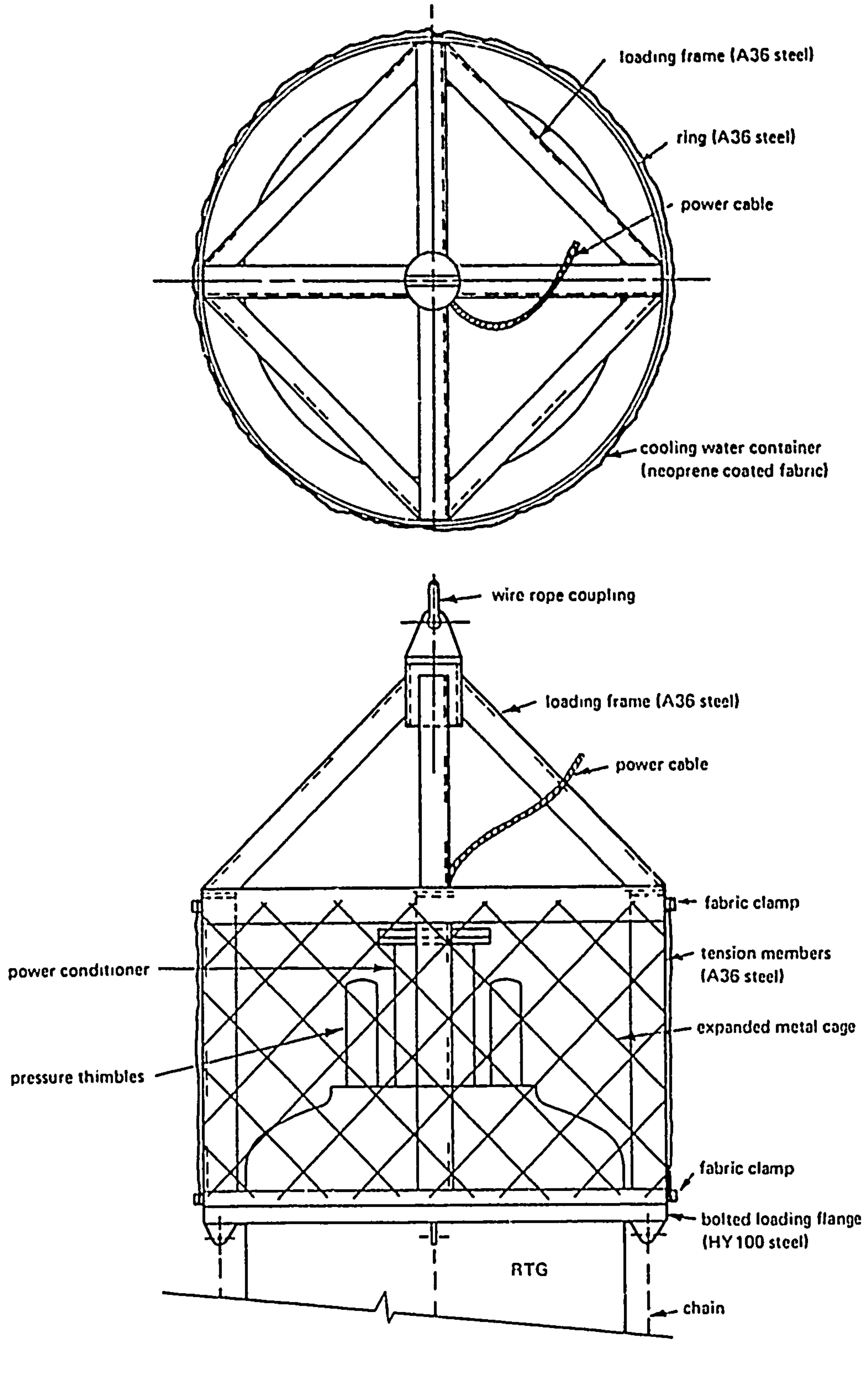
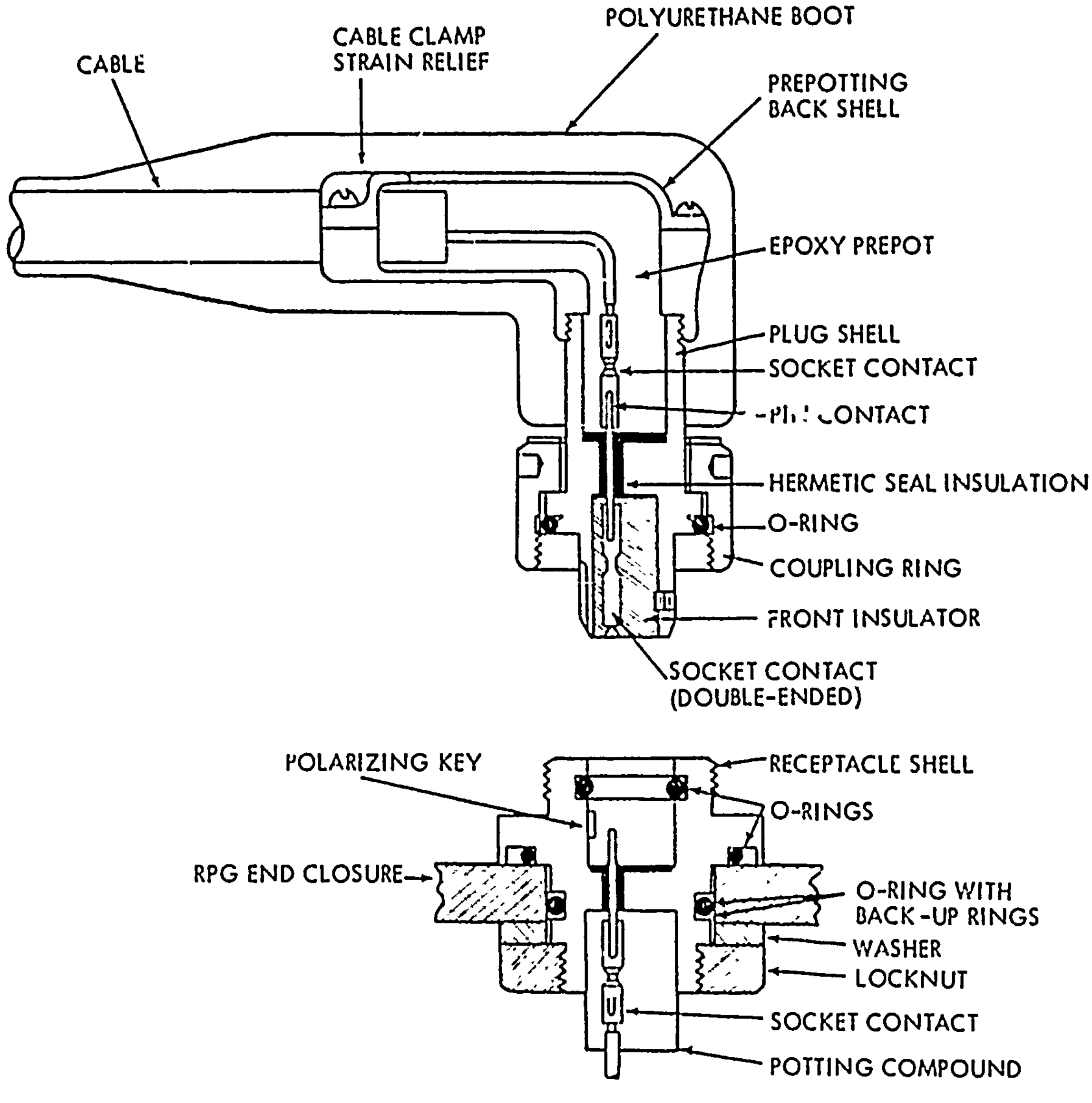


Figure 3.10 Recommended structure (upper).



(FROM REFERENCE 12)

Fig. 3.12 RECOMMENDED 0-20,000 FOOT -DEPTH CONNECTOR

A recall buoy with an anchor will be lowered to the seafloor using a synthetic line. This line should be of sufficient strength to support the weight of the RTG. However, it will be subject to loading only during recovery operations. The synthetic line will be attached to a central top connection point of the RTG. The RTG will then be lowered to seafloor by an electromechanical cable unreeled from shipboard. An electromechanical cable allows monitoring the RTG and mission data during descent.

The electrical load can now be attached to the RTG by one of several methods. A mission cable of equal length to the depth of the site (20,000') is likely here. This requires the simultaneous lowering of electromechanical and mission cables and presents the problem of entanglement of the cables. The electrical load could also be attached underwater using a submersible vehicle or remotely controlled tethered vehicle. A third possibility would be to attach the mission cable to the RTG while both are on-board ship and lower the RTG using the electromechanical cable. The latter two methods will minimize entanglement problems. (See Fig. 3.13).

In these latter two methods the electromechanical cable is not connected to the mission load. It can be connected to either an auxiliary electrical load with a recall buoy, (better suited to a shallow water deployment) or it can be used to trigger an electrical release on a second anchor and recall buoy. The second recall buoy and auxiliary electrical load (or anchor assembly) would then be lowered to the seafloor using a small line which is released once the package is on the bottom. (See Fig. 3.14).

The effect of currents on the cables has not been addressed. Also, the possibility of the cable being buried by sediment has not been addressed. These considerations are significant when considering a 10 year mission lifetime. No maintenance systems have been stated in conjunction with the Isotope Kilowatt program.

3.4 Undersea Site

3.4.1 General

The ocean environment surrounding the emplaced 2KW (e) RTG strongly impacts design requirements and is critical to the RTG's performance and public safety. As a basis for the subject safety and design assessment, an undersea site description assigning values to the most important quantifiable, environmental parameters, was developed and is presented in this section.

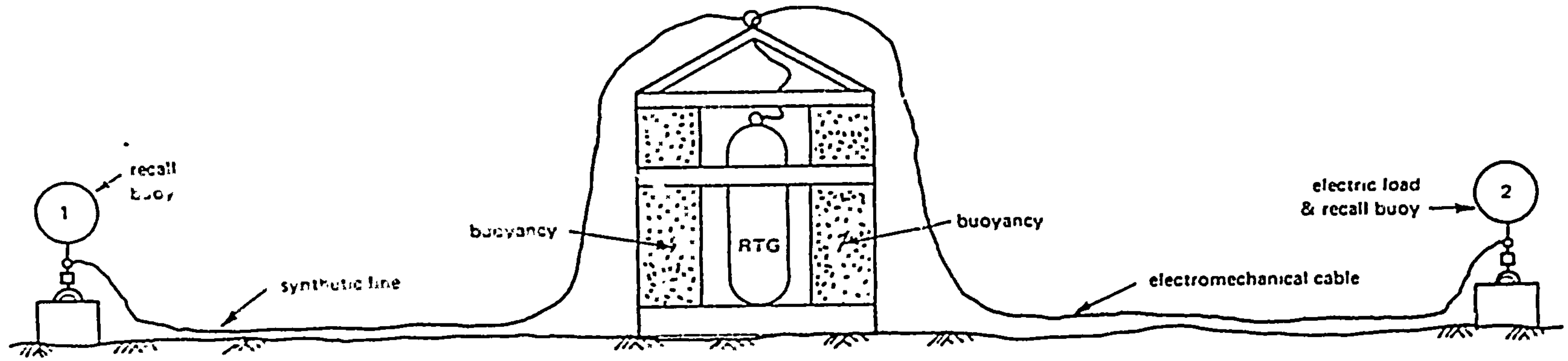


Figure 3.13 Suggested installation configuration.

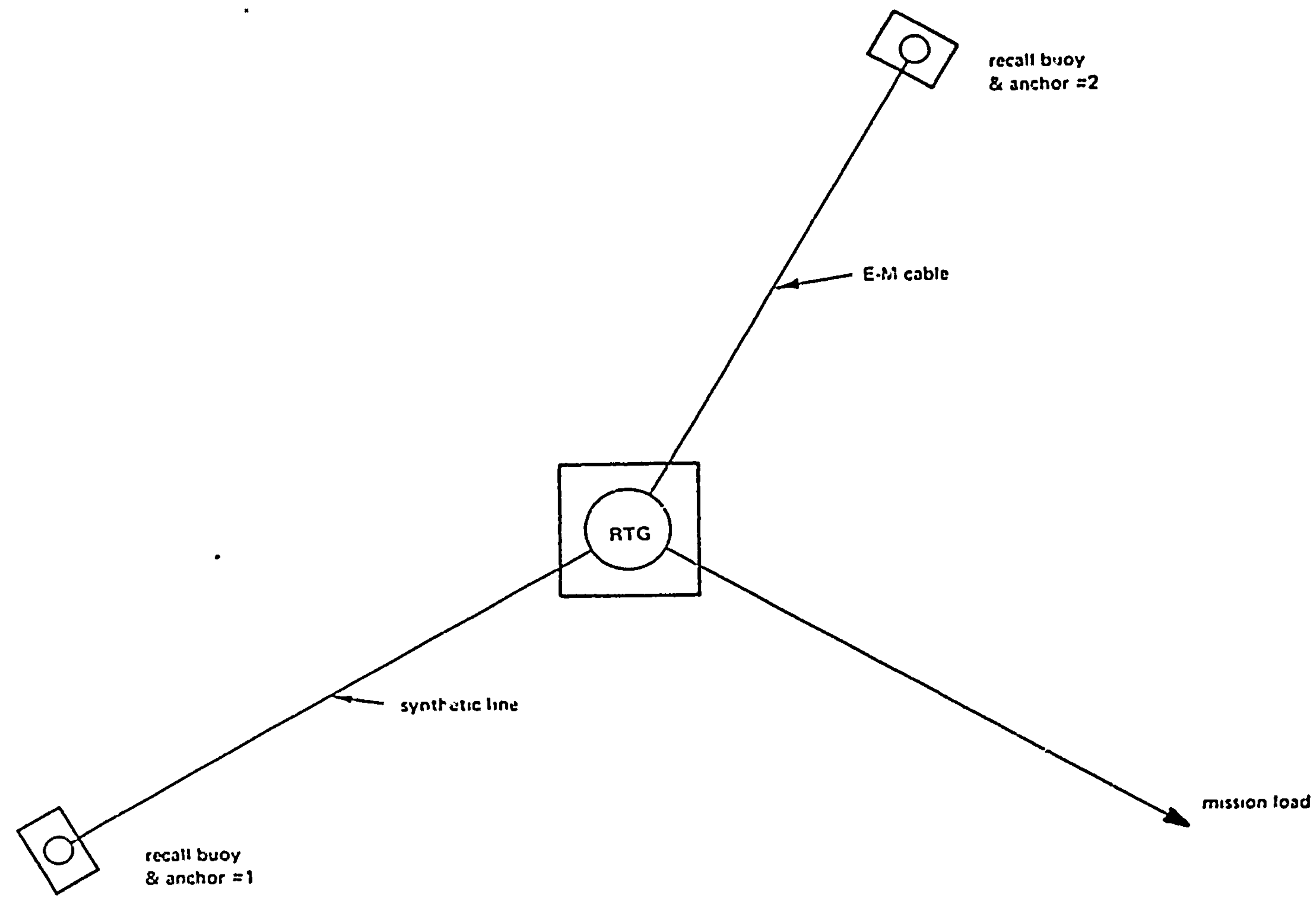


Figure 3.14 Plan view of the RTG system as installed on the seafloor.

In most cases, the site description is based upon a typical worst-case or most critical condition for each parameter and, as a result, does not correspond to any site which actually exists in the ocean. Two parameters, however, are not determined by the worst-case approach. Volcanic activity is so difficult to forecast and the potential hazard so great, that a site requirement must be that the RTG is not emplaced within the influence of any known or suspected volcanic activity. The required bottom bearing strength has been determined as .857 lb./in.^{2}. This was calculated assuming the foundation configuration of Figure 3.9, and is thus consistent with the requirement of covert handling of the RTG.

Selection of a typical worst-case value for a given parameter will depend upon the range of values found in the ocean. Defining what is "typical" depends upon knowledge of deep ocean conditions. The information used in this site description was derived from standard oceanography and ocean engineering data sources. For some parameters, for instance seismicity, not enough data are available to define typical conditions, so that the values used were chosen conservatively. The safety analysis will point-up those areas in which site requirements must be relaxed.

3.4.2 Site Description

a. Depth - 20,000 feet (maximum)

b. Temperature - 1°C (minimum)

c. Salinity - 35 parts per thousand (maximum)

d. Dissolved Oxygen - 5 ml/l (maximum)

e. Bottom Bearing Strength - .857 lb./in.^{2} (minimum)

f. Rate of Deposition of Sediment - .02"/10 years (maximum)

g. Bottom Slope - 4° (maximum)

h. Seismicity - Maximum Horizontal Acceleration - 1.0g

i. Vulcanicity - none

j. Animal and plant life - none

k. Wave Action/Water Current - 12 mph (maximum)

l. Sea-State during Emplacement - 3 (maximum)

3.4.3 Discussion

3.4.3.1 Depth - 20,000 Feet

Depth is the major independent variable since many environmental parameters are correlated to it. Assigning a site depth limits the range of typical temperatures, salinities, dissolved oxygen, fauna and flora, wave action/water currents, etc. Besides being a controlling factor, hydrostatic pressure at depth places some of the most critical demands upon the design. It affects structural and leak tightness requirements and site accessibility for emplacement and retrieval. Site depth was selected as 20,000 feet, the maximum design depth.

3.4.3.2 Temperature - $1^{\circ}C$

Site temperature affects corrosion rates and determines final operating temperature of the RTG components. Deep ocean temperatures vary little with an expected range of $4^{\circ}C$ to $0^{\circ}C$. For the purpose of this evaluation, the site temperature is assumed to be $1^{\circ}C$.

Several locations in the ocean and surrounding seas have very high temperatures near the bottom due to volcanic activity or similar causes. These sites must be avoided as they would result in a degraded conversion efficiency of the thermoelectric modules, and could cause the fusible insulation to melt.

Surface temperatures can vary from $28^{\circ}C$ to just under $0^{\circ}C$. During emplacement and retrieval, the RTG will be subject to these temperatures.

3.4.3.3 Salinity - 35 parts per thousand

The ocean salinity varies in a narrow band near 35 parts per thousand and is important with respect to corrosive effects.

3.4.3.4 Dissolved Oxygen - 5 ml/l

The great bulk of the ocean contains a dissolved oxygen concentration between 1 and 6 ml/l, but 5 ml/l is a typical value for the bottom of the Atlantic Ocean, which compared to other oceans has a high dissolved oxygen content.

3.4.3.5 Bottom Bearing Strength - .857 lb./in.^{2}

As discussed, a foundation-base configuration and total weight has been assumed for the RTG and used to calculate the minimum allowable bottom bearing strength.

3.4.3.6 Rate of Sediment Deposition - .02"/10 years

Some areas, such as those near the mouth of a large river often have deposition rates much higher than .02"/10 years. However, most of the ocean has rates of deposition between .004 and .4 inches per thousand years. Deep-water rates characteristically are very low, so that .02"/10 years is a relatively high rate, barring turbidity currents, and the like.

3.4.3.7 Bottom Slope - 4^{o}

The great majority of the ocean floor has a slope of less than 4^{o}. This is about the average "break-in" slope of the continental shelf.

3.4.3.8 Seismicity - 1.0 g

Earthquakes are known to cause "turbidity currents" which sweep down from the ocean slopes and cover the bottom. These currents are sediment-laden water which can attain speeds of 12 mph. as they sink along the ocean floor. They have been known to leave deposits of sediment 100 feet deep. A turbidity current could completely bury the RTG in sediment. Siting to avoid known or suspected turbidity current areas is necessary to assure containment.

The maximum horizontal acceleration of 1.0 g is very high and is very rare on land. This value was chosen because of a lack of data and the unknown effect of ocean sediment on seismic shifts. (See Appendix E).

3.4.3.9 Vulcanicity

It is assumed that the mission site shall be located far from any underwater volcanic activity. This should not severely limit the usefulness of the RTG but it is necessary due to the extreme environments associated with volcanic activity.

3.4.3.10 Animal and Plant Life

Encrusting organisms are not expected to be a problem on a surface 25 to 30^{o}F hotter than its surroundings.

3.4.3.11 Wave Action/Water Current

The site shall be expected to have a maximum bottom current of 12 mph. This is a high value and average currents are much smaller. The high velocities are associated with the turbidity

currents discussed above. This high value shall be used in analysis to be certain that the RTG can withstand all but the most catastrophic ocean currents. (See Appendix E.)

3.4.3.12 Sea-state during Emplacement

It is expected that the RTG shall be emplaced in a maximum sea-state of 3. The great weight of the RTG and the difficulty of deep-sea installation make emplacement in heavier seas impractical.

3.5 Data Acquisition System

The emplaced RTG will be equipped with a mission package, a performance data acquisition system and possibly, an active retrieval system. None of these items have been defined in the available references. It will be assumed here that the mission package will periodically or continuously relay or transmit the mission data it obtains. If the mission package operates as intended, it will be obvious that the RTG is functioning. However, if the mission package does not operate, it is not necessarily indicative of an RTG failure. It would be desirable to include a separate data acquisition and backup transmission system to provide information on the functioning of the RTG power supply. Valuable RTG parameters that could be monitored are:

1. Output voltage
2. Output current
3. Component Temperatures
4. RTG Attitude
5. Presence of moisture inside the pressure hull.

Such performance data would be most important during the emplacement operation while the RTG is still attached to the emplacement cable and could be easily retrieved in the event of a failure. It is likely that several types of partial failures could be detected and the RTG retrieved before a major failure occurred. This would also increase the reliability of an active retrieval system. For instance, an attitude indicator could warn of a slow tilting of the RTG due to differential compression of the sediment and permit system retrieval before the RTG fell on its side. As another example, if a slow moisture build-up inside the pressure hull due to a slow leak were detected, the RTG could be retrieved before increasing pressure damaged the system.

3.6 Reference Operational Procedures and Responsibilities

3.6.1 Normal

Operational procedures for normal and emergency conditions must be established for each phase of the RTG life cycle. Responsibility for each procedure must also be established. Secondary procedures and backup personnel should be designated to provide for unforeseen circumstances. At the present time, none of the reference documents have delineated complete procedures or responsibilities for the 2KW(e) RTG. However, some useful information is available from procedures established for other RTG's and may be used as a model for this program.

System size, weight, radiation, high temperature and mechanical design place severe constraints upon the procedures. Of these constraints, radiation is the most critical to the public safety. Any handling and/or movement of any RTG must be monitored by personnel trained in radiological safety. The procedures must minimize both danger to personnel and to the public but should not jeopardize performance for success of the mission. The pertinent phases of the RTG life cycle are listed below. The associated discussions should not be considered complete but do indicate the range of procedures required.

3.6.1.1 Assembly and Disassembly

In general, assembly will be carried out under controlled environmental conditions with very little danger to the public safety. The permissible working environment for those assembling the RTG and its components is defined by NRC safety codes. The contractor is responsible for seeing that safety and performance criteria are met during assembly and disassembly.

3.6.1.2 Ground Transportation

Ground transportation shall be conducted over carefully selected routes and by a designated carrier. DOT and NRC regulations on the surface temperature, radiation, size and weight should be followed as applicable.

Active cooling of the assembled RTG is required at all times. Special security precautions should be taken to prevent theft or vandalism of the RTG. Low underpasses should be avoided to minimize the chance of an impact accident.

3.6.1.3 Shipboard Transport

The magnesium bolts that secure the RTG to the foundation present a possible problem that will require precautions during shipboard transport. The damp atmosphere, or contact with the ocean itself will corrode the bolts. This event must be avoided. Several solutions are feasible that will solve this potential problem.

The performance of the RTG should be monitored at all times. The system must be well secured on board. Personnel handling the RTG must be protected from thermal burns.

3.6.1.4 Emplacement and Recovery

Any site testing should be performed as required before emplacement. During emplacement, RTG and mission performance should be monitored at all times. Normal procedures affecting safety and system performance associated with deep-sea emplacement and recovery must be followed.

3.6.2 Emergency

The Navy provided a brief "Emergency Plan for Navy RTG No. 41." This plan, though designed for a much smaller RTG, presents similar considerations to those required for the 2KW(e) RTG. It defines an emergency involving a radioisotope thermoelectric generator "as any event which potentially constitutes a Radiological Accident such as fire,collision, or dropping of the generator so as to do visible external damage, or an event which can be interpreted to be a loss of control over the generator, such as theft or vandalism."

Another reference (OPNAVINST 3040.5 of 28 September 1967) further defines a Radiological Accident to be, "A loss of control of radioactive material which presents a hazard to life, health or property or which may result in any member of the general population exceeding limits for ionizing radiation . . . Included are those events having domestic or international implications and those which may give rise to inquiries by the public or press." The three most credible types of accidents which could lead to a radiological accident as defined above are impact accidents, fires, and loss of control over the generator.

The actions to be taken in case of an accident were then outlined as follows:

3.6.2.1 Impact Accident

An impact accident could occur either during a transportation mishap or when loading or unloading the RTG.

3.6.2.1.1 Make every effort possible to rescue injured or trapped persons and remove them from the accident area.

3.6.2.1.2 When in doubt that the radioactive material is still confined to its container, assume that the immediate accident area is radioactively contaminated and that anyone and anything in the area may be contaminated. Take special care to minimize personal contact with the outer clothing of individuals, the surface of the ground, vegetation, and the surfaces of other material within or removed from the accident area.

3.6.2.1.3 Restrict further access to the accident area from 100 feet in all directions until radiation and spreadable contamination surveys have been conducted. If this impact accident occurs on board the ship, it will not be possible to restrict further access for a distanct of 100 feet; in such a case restrict access for such distance as the ship structure permits.

3.6.2.1.4 It is the normal practice of the U.S. Navy to write a set of notification procedures for each RTG prior to its deployment. In the event of damage to the RTG such that there is any significant increase in external radiation survey readings (above 200 millirem per hour on contact) and/or spreadable radioactive contamination (above 2000 dpm/100 cm^2) on or around the RTG, the notification procedure for this RTG will be implemented immediately.

3.6.3.2 Fire Involving an RTG

A fire could occur either on land or on board the ship. Response:

3.6.2.2.1 Make every effort possible to rescue injured or trapped persons and remove them from the accident area.

3.6.2.2.2 Sound the alarm. Inform the fire department that there is a fire involving a radioisotopic generator. If the fire occurs on board the ship notify the U.S. Coast Guard.

3.6.2.2.3 If the fire is in the vicinity of the RTG, but does not involve the RTG, a reasonable effort shall be made to remove the RTG from the fire area at the earliest possible time without endangering personnel. If the fire occurs on board the ship, this action will probably not be possible.

3.6.2.2.4 If the fire has caused an increase in the ambient temperature in the vicinity of the RTG, and the RTG has not suffered any visible external damage, then the RTG should be kept cool with water spray. If the fire occurs during shipment, then the RTG should be kept cool with water spray, if possible.

3.6.2.2.5 Fight the fire as though toxic chemicals are involved. To the extent possible keep upwind from the fire and avoid smoke, fumes and dust. Segregate clothing and tools used at the fire until they can be checked for radioactive contamination before being returned to normal use. (This monitoring will not be necessary if radiological safety personnel determine that there has been no compromise of the RTG fuel containment.) The Radiological Safety Officer or his assistants will provide film badges or pocket dosimeters to all fire fighting and other rescue personnel involved in the operation as soon as practical. If the fire occurs on-board the ship, the ship should be turned so that it is headed in a direction such that personnel will be upwind from the fire.

3.6.2.2.6 Fire department personnel shall be trained in the use of both the portable radiation survey instrument and personnel dosimetry and ensure the availability of instruments for update training. In the absence of radiological safety personnel, fire department personnel shall monitor the area surrounding the RTG during and after fire fighting operations. If radiation dose rates in excess of 200 millirem per hour are encountered, RTG container damage shall be presumed to have occurred. The procedures described in paragraphs 3.6.2.1 above, shall be implemented after fire fighting operations have been completed.

3.6.2.3 Loss of Control of an RTG

Loss of control could occur due to vandalism or theft at any time, or due to a mishap on-board the ship resulting in the RTG falling overboard. Response:

3.6.2.3.1 Determine the current status of the RTG insofar as practicable.

3.6.2.3.2 Determine the last known geographical location of the RTG as accurately as possible, together with any information that may be helpful in determining its present location.

3.6.2.3.3 Implement the notification procedures described below:

The Notification Procedure lists those persons to be informed of the accident and how they can be contacted.

3.6.3 Summary

3.6.3.1 The operational procedures and responsibilities for normal and emergency conditions associated with all phases of the 2KW(e) RTG system are not presently defined in the reference documents.

3.6.3.2 The size, weight, complexity and large radioisotope inventory of the system imply that safety will require a greater effort than for previous RTG systems.

3.6.3.3 It is recognized that RTG design and safety procedures are strongly interrelated and should be developed as parallel efforts.

REFERENCES

1. ORNL-TM-2366 "Isotope Kilowatt Program Task 1-Conceptual Design and Evaluation".
2. ORNL-TM-2959 "Reference Design for a Thermoelectric Isotope Power Plant Unit Employing Heat Pipe Modules".
3. ORNL-TM-3213 "Comparison of Nickel and Iron Heat Block-Shields".
4. ORNL-TM-3230 "Fueled Capsule Design and Evaluations - A Safety Analysis".
5. ORNL-TM-3604 "Effect of Ambient Pressure on the Design of the Thermoelectric and the Organic Rankine Cycle Systems for the Isotope Kilowatt Program".
6. ORNL-TM-3806 "Thermal Test of the Heat Block Shield for the Isotope Kilowatt Program".
7. ORNL-TM-4012 "Test of a Combined Heat Pipe - Thermoelectric Module".
8. ORNL-TM-4102 "Performance of Aluminum Screen and Foil as a Thermal Fuse and Insulation for Isotope Power Plants".
9. ORNL-TM-4350 "Isotope Kilowatt Program Fuel Capsule Testing".
10. ORNL-TM-4422 "Full-Scale Fusible Insulation Evaluation Test"
11. NSRDC "Preliminary Designs and Cost Estimates of Pressure Hulls for the Conatinment of a Portable Nuclear Electric Power Plant".
12. NSRDC "Pressure Test of Two Fuel Capsules".
13. NCEL-N-1304 "Technical Investigation Supporting a 2KW(e) RTG Final Design".
14. NCEL-N-1359 "Radioisotope Thermoelectric Generator Heat Transfer Design and Proof Tests".
15. WAI-104 "An Environmental Assessment for the Use of Radioisotope Power Generators".
16. NOLTR 74-33 "Design Guide for Radioisotope Power Generator Pressure Vessels".
17. WANL-PR(EEE)-055 "Compact Thermoelectric Converter Systems Technology Final Report".
18. WANL-PR(EEE)-056 "Compact Thermoelectric Converter Program GFY 1974 Summary Report".
19. WANL-PR(EEE)-057 "Tubular Thermoelectric Modules/Isotope Kilowatt Program Interim Report".
20. ORNL Report "Evaluation of Production of 34-KW (th) Strontium-90 Fueled Heat Source Assemblies at Oak Ridge National Laboratory".

4.0 Accident Identification - Failure Mode and Effects Analysis

4.1 Assembly

4.1.1 Assembly of the Sources into the Heat Block Shield

The Strontium Ortho-Titanate fuel remains within the protective confines of the Isotope Facility until it is safely sealed into the Hastelloy C-276 capsules. The starting point for the accident analysis is the encapsulated fuel. Each capsule weighs in excess of 100 lbs. and generates 4860 Watts (th). The capsule equilibrium temperature in 70^{O}F still air is about 800^{O}F. The rate of temperature rise is less than .55^{O}F/sec. The rate of rise is slow enough that there is no need to use heat sink mandibles on the capsule manipulator. A heat source can be removed from the heat sink and inserted into the heat block-shield with remote manipulators. Since the fuel capsules are designed to withstand the 30 ft. drop test (Appendix F), there is no potential radiation hazard if they are dropped during handling.

After the seven heat sources are in place in the heat block-shield, the upper heat block-shield plugs are inserted using remote manipulators. The source-shield subassembly may then be removed from the remote handling area and the plugs may be welded in by hand. The weld plugs provide secondary barriers to the possible dispersion of radioactivity and will maintain the sources within the heat block shield under any credible accident scenarios.

The source-shield assembly weighs 16,500 lbs. and has a rate of temperature rise of .05^{O}F./sec. If exposed to still air, the equilibrium surface temperature will be 480^{O}F. (assuming 86^{O}F ambient temperature). This maximum temperature would be approached later than 2.7 hours after loading. The principal hazard existing at this time is contact burns from improper handling. Table 4-1 is a summary of failure modes and effects associated with the assembly of the heat block-shield at the Isotopes Facility.

4.1.2 Assembly of the Source-Shield and the RTG Subassembly at the Dock Facility (a b 1 c 3)

The source-shield assembly will arrive at the Dock Facility by commercial carrier. It may be off-loaded onto a wheeled vehicle and transported into the facility to a location within reach of a crane for handling the assembly. The RTG subassembly, composed of the pressure vessel, heat pipes, thermoelectric units, and fusible and non-fusible insulation, will also arrive by commercial carrier. Since this assemblage contains no energy sources, it only constitutes a safety hazard with respect to dropping or rolling. An assembly jig, designed to provide alignment during assembly

TABLE 4-1

Failure Mode and Effects Analysis for Source-Shield Assembly

Component	Failure Mode	Probability x=possible o=unlikely	Effect	Required Response or Correction
Heat Source Capsule	Dropping, immediate recovery	x	Capsule dented, scratched, fuel capsule will sustain 30 ft. drop test per NRC/DOT requirements	Use proper manipulator mandibles, Limit drop distance to 30 ft.
	Dropping, delayed recovery	o	Capsule dented, scratched, Heat up to 800°F	Institute immediate recovery or provide heat sink catcher tray
	Heat sink failure	o	Overheating of capsules	Provide monitoring of heat sink condition - provide standby emergency cooling
	Thermal expansion cracking	o	Rupture of welds or housing	Provide proper allowance for differential expansion
	Poor heat coupling	o	Part of ceramic fuel form undergoes phase transition	Provide close tolerance fit between fuel and housing
	Radiological hazard	o	Excessive dose	Assemble with adequate shielding and remote manipulators, Institute personnel control

TABLE 4-1 (cont'd.)

Component	Failure Mode	Probability x=possible o=unlikely	Effect	Required Response or Correction
Heat Block-Shield	Dropping	x	Personnel injury	Pretest cables, Institute personnel control, Define assembly procedures
Source-Shield Assembly	Radiation streaming through plug welds	o	Excessive dose to personnel	Step the shield plugs tc eliminate streaming paths
	Burns	x	Thermic injury to personnel	Provide cooling and/or personnel guards
	Fire	o	Capsule over temperature	Maintain adequate fire control at all times.
	Self-heating	o	Capsule Melting	Do no allow the assembly to overheat
	Dropping	x	Personnel injury	Pretest lifting cables, Institute personnel control

of the various components will be necessary.

Care must be exercised during the RTG assembly process to prevent dropping or rolling of heavy equipment. The radiant heat flux from the source-shield assembly will be noticeable to nearby personnel but constitutes no safety hazard. However, direct tissue contact with the source-shield assembly does present a substantial burn hazard. Third degree burns would occur from contacts of less than one second.

The source-shield temperature will begin to rise as soon as the insulation is installed. However, the very slow rate of rise allows time for the assembly if the fit of all components has been pretested and procedures have been practiced. Excessive delays during this process would allow premature melting of the fusible insulation.

Insertion of the heat pipes into the heat shield block is a difficult installation procedure. All twelve heat pipes must be simultaneously inserted into the heat block holes. The heat pipe walls are only 0.083 in. thick and may be easily damaged by any lateral or twisting movement. The thermoelectric modules must be actively cooled at all times. The final assembly prosess is the sealing of the pressure vessel. Performance and integrity tests are then performed. The RTG is then ready for transport to the mission site.

Table 4-2 is a failure mode and effects analysis for the assembly of the RTG at the Dock Facility.

4.2 Pre-loading Operations

4.2.1 Handling

An electric crane is probably the most practical way to handle the assembled RTG. Cranes capable of handling this weight are fairly common. All standard safety procedures such as dead weight testing and personnel control should be instituted.

4.2.2 Thermal Control

The RTG must be kept at or below its operating temperatures. In normal operation, approximately 90% of the heat output is transferred through the TE thimbles and 10% is lost through the fusible insulation on the sides of the RTG. The designed operational heat block-shield surface temperature is 1150^{o}F

TABLE 4-2

Failure Mode and Effects Analysis for Assembly at the Dock Facility

Component	Failure Mode	Probability x=possible o=unlikely	Effect	Required Response or Correction
Foundation	Dropping	x	Personnel injury	Pretest cables, Institute personnel control
	Flexure	o	Long-term fatigue of pressure vessel and possible leaking	Design the foundation for vertical thrust support of the RTG
Heat Source-Shield Assembly	Dropping	x	Personnel injury	Pretest cables, Institute personnel control, Design assembly for safety
	Ionizing Radiation	o	Personnel injury	Insure proper shield design, Institute personnel control
	Burn	x	Personnel injury	Provide cooling of source-shield assembly, protective clothing, personnel control
Fusible Insulation	Dropping	x	Personnel injury	Pretest cables, Institute personnel control
	Burn	x	Personnel injury	Provide cooling of source-shield assembly, protective clothing, personnel control
Upper Pressure Vessel Assembly	Dropping	x	Personnel injury	Pretest cables, Insure safe design of lifting supports, Design for minimum human steering
	Rupture of one or more heat pipes	x	Personnel injury from potassium vapor	Provide adequate ventilation Design for guided insertion of heat pipes, Control positioning of pressure vessel components during assembly

TABLE 4-2 (cont'd.)

Component	Failure Mode	Probability x=possible o=unlikely	Effect	Required Response or Correction
Upper pressure vessel assembly (cont'd.)	Cascading heat pipe failure from improper gradient	o	Overheating, potassium release	Design heat paths to avoid hot spots
Complete RTG	Dropping	x	Personnel injury	Pretest cables, Insure safe design of lifting fixtures, Institute personnel control
	Cracked Welds	o	Leak in pressure vessel	Don't lift RTG by the top, lift by the foundation
	Overheating due to cascade heat pipe failure	o	Personnel injury, TEM damage	Provide emergency cooling for sidewalls so fusible insulation will not melt
	Steam pressurization and puff release	o	Personnel hazard	Use pressure relief until insulation is dry or before final sealing, assemble in dry atmosphere

and the upper limit on the fusible alloy temperature is 1715°F. Slight changes in the thermal inventory or the conductances of the various heat flow paths could result in premature melting of the fusible insulation. It is essential that the TEM thimbles be cooled on a continuous basis. The large thermal inertia of the system allows the cooling to stop for short times such as for transfer to a different cooling system. However, any delay at this time will melt the insulation and abort the mission. The RTG side walls may be cooled to also eliminate the potential personnel burn hazards associated with the RTG on shipboard.

4.2.3 Storage

The RTG should be stored in a secure area to maintain control over its large radioisotope inventory. The cooling requirements for storage are even more important than those for handling since emergency action might not be so quickly taken. One possible storage environment would be water immersion. The tank should be large enough to absorb the waste heat with natural heat transfer processes. If the facility is unsuitable for this, heat exchangers such as those used for handling would also be required for storage. Continuous automatic monitoring of the RTG power output would be valuable since a rise in power output would be indicative of an internal overheating condition. Similarly, a drop in power would indicate insulation deterioration or a rise in cold junction temperature. Any substantial variation in power output should activate an alarm system.

4.2.4 Tests

The RTG subassemblies should be extensively tested to establish satisfactory long-term operation of the pressure vessel, heat pipes, TEM's and associated electrical connections. The TEM tests should be sustained for sufficient time periods to establish the degradation rates due to tellurium diffusion Such tests will use simulated electric powered heat sources in a partial or whole mock-up of the source-shield block.

Three final steps are required to prepare the RTG for operation (1) Interior gases and vapors must be evacuated and replaced by an inert atmosphere, (2) the system must be leak tested to establish that all joints and seals are within mission requirements. It is also desirable that the system be hydrostatically tested at approximately operating pressure to examine the effect of any pressure vessel flexure on the leak rates.

Table 4-3 presents a failure mode and effects analysis adapted to present key milestones in this section.

4.3 Transportation

4.3.1 Land Transportation of the Source-Shield Assembly

The heat sources will be installed into the heat block-shield at the Isotopes Facility. This 9 ton assembly will heat to about 500°F. It does not present a radiation hazard inasmuch as the shield is designed to meet all applicable NRC and DOT transportation ionizing radiation requirements. It may be transported to the Dock Facility by either truck-trailer or by railroad car. Accident analyses show the probability of a severe accident is approximately the same for either mode. The source-shield assembly will be loaded onto the carrier by crane using suitable lifting harnesses attached to lifting fixtures designed and sized for the task. Heat conduction through the RTG support base into the carrier bed as well as thermal radiation may cause the carrier to exceed DOT temperature limits outside of the package boundary. Because the source-shield assembly presents a burn hazard and exceeds DOT temperature specifications, the package boundary will be set by a mesh guard structure which provides burn protection and meets the 180°F transportation requirements. The hot rising air currents will cause the upper part of the guard structure to exceed 180°F. Some baffling must be provided to mix cooler air in with the hot air. The source-shield assembly will be tied to the carrier in a conventional fashion using tie down tendons meeting Federal regulations. Due regard should be given for the heat conductivity of the tie down device if it exceeds the guard-shield boundary.

During transportation, the carrier should follow standard procedures for the shipment of radioactive material. The carrier will call periodically as required and follow the preassigned route. Possible accidents along the route are analyzed.

Upon arrival at the dock facility, the source-shield will be unloaded by one of several standard loading procedures. A crane may be used to set it on a wheeled carrier for transportation to the assembly area where it will be incorporated with the pressure vessel assembly to become the 2 KW(e) RTG.

Table 4-4 presents a failure mode and effects analysis of events associated with these tasks.

TABLE 4-3

Failure Mode and Effects Analysis for RTG Handling, Storage and Tests at the Dock Facility

Phase	Failure Mode	Probability x=possible o=unlikely	Effect	Required Response or Correction
Handling	Dropping	x	Personnel injury	Provide cable and crane preload test, Institute personnel control
	Partial overheating	?	Melting of fusible insulation	.ool sidewalls of RTG
	Overheating	?	Damage to TEM	Maintain RTG at or below design ambient temperature (75°F) at all times, Use alarms to warn of out-of-limit conditions
	Collision	o	Damage to RTG, especially the TEM thimbles	Handle the RTG in a controlled area separate from other activities
	Loss of electrical load	x	Damage to TEM, and fusible insulation	Maintain an electrical load on the TEM at all times
Storage	Partial overheating	?	Melting of fusible insulation	Cool sidewalls of RTG, Maintain on-call emergency crew
	Overheating	?	Damage to TEM	Maintain RTG at design cold temperature (75°F) at all times, use alarms to warn of out-of-limit conditions
	Collision	o	Damage to RTG especially TEM thimbles	Store RTG in an exclusion area

TABLE 4-3 (cont'd.)

Phase	Failure Mode	Probability x=possible o=unlikely	Effect	Required Response or Correction
Storage	Loss of electrical load	x	Damage to TEM and fusible insulation	Maintain electrical load on TEM at all times
Test	Electrical Wiring	x	Wiring failures may cause TEM overheating and failure	Institute quality control procedures, assure that wiring connections suitable for working environment, all wiring secure against vibration, Institute resistance tests, load tests, aging tests and efficiency tests
	Heat Pipes	x	Overheat TEM's, failure to accomplish mission	Institute quality control procedures, assure integrity of heat conduction paths, Provide containment getters, Provide strain relief design to avoid non-design stress on heat pipes.
	Pressure Vessel leakage	x	Delays or failure to accomplish mission	Institute quality control over construction and assembly, provide for visual and ultrasonic inspection of joints, Measure Leak Rate at atmospheric and Helium operating pressure
Out-gassing	Failure to remove undesirable gases, vapors, or condensibles	o	Accelerated corrosion of the SAE 1010 steel heat block in the heat pipe holes-heat pipe failure-termination of mission by fusible insulation melting	Remove undesirables and refill with inert gas.

TABLE 4-4

Failure Mode and Effects Analysis for Land Transport of the Source-Shield Assembly (SSA)

Phase	Failure Mode	Probability x=possible o=unlikely	Effect	Required Response or Correction
Loading and Preparing for Transport	Dropping	x	Personnel injury	Design proper lifting fixtures taking into account an operating temperature of 500°F
	Burns from SSA contact	x	Personnel injury	Personnel control, Protective clothing, Exclusion zone, Use active liquid or gas cooling of SSA
	Burns from guard shield	x	Personnel injury from contact temperatures exceeding 49 CFR 173.393	Use active liquid or gas cooling of SSA
	Burns from transportation vehicle	x	Personnel injury from contact temperatures exceeding 49 CFR 173.393	Use active liquid or gas cooling of SSA or use low heat conduction base and radiation shields
	Burns from tie-down cables	x	Personnel injury from contact temperatures exceeding 49 CFR 173.393	Use active liquid or gas cooling of SSA or use heat insulators on cables

TABLE 4-4 (cont'd.)

Phase	Failure Mode	Probability x=possible o=unlikely	Effect	Required Response or Correction
Transport	Burns from guard shield, Transportation vehicle or tie-down cables	x	Personnel injury from contact temperature exceeding 49 CFR 173.393	Use active liquid or gas cooling of SSA
	Severe collision, rollover, etc.	o	Personnel injury, environment impact possible but not probable, damage to SSA	Specify moderate transportation speeds.
	Fire	o	Personnel injury, possible environmental impact, Damage to SSA	Specify moderate transportation speeds.
	Water submersion	o	None	Avoid transportation near or in deep water, If possible; retrieve SSA
	Partial Burial	o	None	Retrieve SSA
	Fall off	o	Personnel injury, Damage to SSA	Include adequate safety factors in cables, support base, tie-down fixtures
Unloading	Burns from SSA guard shield, Vehicle or tie-down cable	x	Personnel injury	Use active liquid or gas cooling of SSA
	Drop	x	Personnel injury, damage to SSA	Pretest lifting equipment and fixtures, institute personnel control.

4.3.2 Sea Transportation

Upon completion of assembly and performance tests, the RTG will be lifted by crane, loaded onto a wheeled carrier and transported to dockside. There a vessel of the T-AGOR-16 type will lift it by means of a ship-mounted crane and locate it on deck, in a low traffic area. The RTG will be rigged to the deck using cables and/or deck clamps to the foundation. The TEM's must be maintained at or below their maximum operating surface temperature of 75°F by heat exchangers. The condition of the RTG should be continuously monitored by measuring the output power into the mission load or a dummy load. If the power varies from the allowable limits an alarm should warn of this condition.

The hazards of transporting the RTG shipboard to emplacement site are comparable to those of transporting any 10 ton load in a similar manner with the added hazard of contact burns to personnel if the RTG sidewalls are not cooled The various failure modes and anticipated effects are summarized in Table 4-5

4.3.3 Emplacement

Upon arrival at the mission site, the emplacement process begins. Emplacement will not be executed unless the ocean is ralatively calm (Sea State #3 or less). The winch, crane and emplacement cable must be dead weight tested in excess of the anticipated load. The winch is given a final inspection and the cable is attached to the RTG lifting fixture. The tie-downs securing the foundation and RTG to the deck are removed. RTG power is transferred to the mission loop.

The RTG with its Ocean System are lifted off the deck and into the sea. When the RTG is partially submerged, the auxiliary heat exchanger is removed. The thimbles must be submerged in seawater shortly after disconnecting the heat exchanger to avoid TEM damage and activation of the fusible insulation. The winch used for this operation should be of the constant tension type. Thus, the rolling of the vessel in the sea results in minimum tension variations.

The emplacement cable is extended until the RTG reaches the seabed. During emplacement, there must be no transverse ship velocity that could turn over the RTG. When it contacts the seabed, drift is counteracted by control of the ship propellers. After the seabed is contacted, the actual position of the system should be determined. The emplacement cable must then be disconnected either at the RTG or the ship. If detached at the ship, a drag device should be installed to prevent the falling cable from fouling the RTG or Mission Package.

TABLE 4-5

Failure Mode and Effects Analysis for Sea Transportation

Phase	Failure Mode	Probability x=possible o=unlikely	Effect	Required Response or Correction
Loading Aboard Ship	Dropping	x	Personnel injury, Equipment damage	Cable and crane preload test, Personnel control
	Partial Overheating	?	Melting of fusible insulation, Personnel burns	Cool sidewalls of RTG or implement manual seawater spray
	Overheating	?	Damage to TEM	Maintain RTG in design cold ($75^{\circ}F$) temperature environment at all times, Provide an alarm for out-of-limit conditions
	Collision	x	Damage to RTG especially TEM thimbles, Possible failure of heat removal system	Plan RTG loading with consideration of accidental swing impact points. Control other area activities to not interfere with RTG loading. Implement emergency manual sea spray
	Loss of electrical load	x	Damage to TEM	Maintain electrical load on TEM at all times
	Dropping foreign object	x	Damage to RTG, Possible failure of heat removal system	Control lifting of objects above RTG. Implement emergency manual sea spray

TABLE 4-5 (cont'd.)

Phase	Failure Mode	Probability x=possible o=unlikely	Effect	Required Response or Correction
Sea Transportation	RTG slips its mooring in high seas	x	Personnel injury, failure of heat removal system, Damage to RTG and equipment	Redundant conservative rigging and hold-down brackets, Keep crane loosely attached to RTG lifting fixtures
	Deck foundation failure	o	Personnel injury, Failure of heat removal system, Damage to RTG and equipment	Check deck for adequate support and reinforcement, Keep crane loosely attached to RTG lifting fixtures
	Hot sides	x	Personnel burns	Keep all exposed parts of RTG below 120°F, Use guards
	Collison with foreign object	x	Damage to RTG, Damage to heat removal equipment, Overheating	Control ship activity around RTG, If overheated, use emergency seawater spray
	Collision with another vessel	o	Ship sinks, Personnel injuries, Damage to RTG and equipment, Failure of heat removal	Heat removal failure activates emergency cooling, No anticipated environmental impact since RTG designed for seawater immersion, Don't sail ship over water deeper than RTG design depth (20,000 ft.)

The failure modes for RTG emplacement are primarily those associated with any emplacement on the seabed of a device of about 10 tons. If the emplacement cable should break, however, the center of gravity of the RTG and foundation may be above the maximum drag point (depending upon foundation design) and hence cause the assembly to invert. The heat pipes are designed for 0 to 90° (horizontal) tilt operation. Any greater tilt would cause heat pipe shutdown. The foundation covers a larger area than the cross section of the RTG, so that the unit would come to rest at an angle greater than 90° to the vertical. The TEM thimbles would probably be buried in silt, on impact. Additionally, the impact loads may be sufficient to damage the TEM thimbles and cause a leak. In practically all of these scenarios, the mission would be a failure and the RTG may leak seawater. Recovery of the RTG in this inverted, possibly buried condition would be extremely difficult.

These failure modes and effects are summarized in Table 4-6

4.4 Mission Execution

4.4.1 Operation

The properly emplaced RTG should operate continuously for its design lifetime of 10 years without mishap. Sites deeper than about 3,000 feet will not have any problems with marine growth. The average deep ocean sedimentation rate is 0.02"/10 years and hence of no operational or safety consequence. It may be possible for seismic action to topple the RTG from its foundation, causing heat pipe shutdown and possibly damaging the TEM thimbles allowing seawater to leak inside the Pressure Hull.

Possible operational failures due to RTG design and/or construction are: leakage around the main joint seals, any electrical or pneumatic connectors or electrolytic action on the TEM thimbles.

These and other potential accidents are considered in Table 4-7.

4.4.2 Maintenance

No maintenance is possible without recovery. Post-recovery maintenance on shipboard will probably be limited to external connectors and the mission package. Opening the RTG on board ship is not considered acceptable due to the potential radiological hazard and the danger of heat pipe breakage.

TABLE 4-6

Failure Mode and Effects Analysis for Emplacement

Component	Failure Mode	Probability x=possible o=unlikely	Effect	Required Response or Correction
Cable/Winch Failure	Cable whiplash	x	Personnel injury due to cable whiplash	Pretest cables, Insure personnel protection, Establish personnel control
	RTG free fall in seawater, Impact with Seabed	x	Possible damage to RTG, No environmental impact if it does not turn over	Terminal velocity in water is less than 30 mph - corresponds to an airdrop of 15 ft. which source-shield can withstand, Provide impact protection for TEM thimbles
	RTG free fall in seawater, Impact with Seabed	x	RTG turns over and lands on side or upside down	Use a drag screen above RTG having more drag than the foundation
	Drop on deck	x	Personnel injury	Pretest lifting harness or fixtures
Leak	Crack RTG seal(s)	x	Stress corrosion cracking accelerated failure	Lift RTG by its foundation to avoid stress on seals
RTG foundation	Cable drag-induced turnover	x	RTG turns over, mission failure	Keep emplacement vessel fixed relative to seabed site
Cable fouling	Cable and mission cables become entangled	x	Possible mission failure	Use a separate mission guidance line from support vessel or a technique of active mission deployment

TABLE 4-7

Failure Mode and Effects Analysis for Operation

Initiator Class	Failure Mode	Probability x=possible o=unlikely	Effect	Required Response or Correction
Environmental	Earthquake	o	Topple RTG from foundation, Failure of heat pipes, Failure of pressure vessel integrity	Design foundation for maximum credible accelerations, Use guards on TEM thimbles
	Marine growth	o	May insulate TEM thimbles causing overheating or RTG body reducing emergency cooling effect	Site to avoid this problem
	Vulcanicity	o	Insulate RTG causing overheating, Direct overheating from lava flow	Site to avoid this problem
	Tubidity Currents	o	Insulate and topple RTG - overheating	Site to avoid this problem
	Sediment scour and deposition	x	Tends to insulate RTG - overheating	Site to make negligible
	Sinking ship or submarine	o	Crushes RTG, causes fuel release	Site to make negligible
	Dredging or commercial activity	o	Topple RTG from foundation, Failure of heat pipes, Failure of pressure vessel integrity	Site to make negligible

TABLE 4-7 (cont'd.)

Initiator Class	Failure Mode	Probability x=possible o=unlikely	Effect	Required Response or Correction
Pressure Vessel Failure	Slow sea-water leak at pressure vessel seal, TEM thimbles, or mechanical-electrical feed-throughs	x	Mission failure, Reduction of fusible insulation to aluminum chloride which goes into water solution, Moisture impregnates non-fusible insulation, Electrolysis of heat block-heat pipe junctions-heat sink junctions, Corrosion of shield plug welds, Corrosion of fuel encapsulation, Failure of heat pipes due to steam pressure	Quality control and inspection, Recovery soon after power drop
	Fast seawater leak	o	Sudden quench of the shield block fails block and/or weld seals of shield plugs in block. Pressure fails heat pipes but source-shield does not overheat	Use malleable steel for shield block
	Intermediate Seawater leak	o	Sudden quench and pressure buildup sufficient to crack heat block and crush heat pipes, High temperature corrosion of fuel encapsulation exposed to seawater resulting in radioactive material release in less than one year	Use malleable steel for shield block

4.4.3 Recovery

The recovery method is not presently defined by the Reference Documents. It is assumed that some form of grappling system will be used. The chosen method must ensure that a positive connection between the RTG and the recovery cable is made and maintained through the lifting stage. The cable is then slowly retrieved as the vessel is maneuvered directly above the RTG for a vertical lift off the foundation (which is left behind). The magnesium bolts will be disintegrated due to corrosion, thus allowing the RTG to be recovered as a lighter load without the problem of pulling the foundation free of the seabed.

The most serious accident that could occur during recovery is cable or hook breakage. If the recovery cable breaks, it will probably not be possible to retrieve the RTG. Additionally, the RTG may be damaged and leak from the fall. All efforts should be directed to maintaining the hard link between the RTG and the ship. If the RTG had developed a slow leak over a long period and is in equilibrium with the seabed pressure, the rapid pressure change on recovery may cause the pressure hull to explode in the ocean or even on board ship. A method of pressure relief is required.

These and other failure modes and their effects are summarized in Table 4-8

4.4.4 Ultimate Disposition

Immediately after the RTG is recovered from the ocean, an auxiliary heat removal system must be connected. After securing of the RTG to the vessel, the sea voyage back to a designated dock may begin. Upon arrival at dockside, the RTG will be lifted by ship's crane from the deck to a wheeled carrier at the dock. The RTG will then be transported to the Dock Facility for disassembly.

At the Dock Facility, the RTG is carefully inspected for physical damage and radiation leaks. If it is still operational, final tests may then be performed. Upon completion of the inspection, the pressure vessel main seal may be opened. Monitoring for abnormal radiation levels should be continuous during disassembly. The heat source-shield is removed from the pressure vessel and loaded onto a wheeled vehicle to be transported to a designated vehicle for the return trip to the Isotopes Facility.

At the Isotopes Facility, the welds holding the shield plugs in place are ground out and the heat source-shield is transported to a hot cell. Manipulators are used to remove the shield plugs, extract the heat sources and deposit them on a heat sink.

TABLE 4-8

Failure Mode and Effects Analysis for Recovery

Component	Failure Mode	Probability x=possible o=unlikely	Effect	Required Response or Correction
Grappling hook	Fails to make adequate connection	x	Partial lift of RTG then drop, RTG may land on its side and overheat, Relocation and recovery may be difficult or impossible	Measure the lifting force, Assure adequate grip
	Breaks during lift	x	-Same as above-	-Same as above-
	Breaks before lift	x	Drop line	Replace hook, Emplacement line may be more tangled than when originally emplaced
Grappling cable	Breaks during lift	x	Partial lift of RTG then drop, RTG may land on its side and overheat, Relocation and recovery may be difficult or impossible	Measure the lifting force, Assure adequate grip
	Breaks before lift	x	Drop line	Replace line, Emplacement line may be more tangled than when originally emplaced
Lift Angle	RTG fouls on foundation or bottom material	x	Recovery line breaks, RTG remains on foundation , if RTG falls off of foundation may land on side and overheat	Design foundation release and restraint so that considerable latitude is allowable on the lift angle, Base of RTG should be designed to minimize possibility of fouling on bottom material if it is dragged along bottom as cable is taken up.

TABLE 4-8 (cont'd.)

Component	Failure Mode	Probability x=possible o=unlikely	Effect	Required Response or Correction
RTG Pressure Vessel	Vessel cracks	o	RTG fills with water up to 10,000 psi	Lift by bottom of pressure vessel not top, Very unlikely for pressure vessel crack to propogate over a few inches before pressure is relieved, Provide pressure relief device

After inspection, the heat sources are sent to a high level waste storage facility or may be reprocessed into new heat sources depending upon economics and new mission requirements. The other components of the RTG will be decontaminated if necessary, inspected as to mission performance and restored to service or salvaged depending on requirements and economics.

Table 4-9 presents a failure mode and effects analysis for ultimate disposition.

TABLE 4-9

Failure Mode and Effects Analysis for Ultimate RTG Disposition

Phase	Failure Mode	Probability x=possible o=unlikely	Effect	Required Response or Correction
Handling			Refer to Table 4-5	
Disassembly	Steam release	x	Personnel burns	Anticipated problem, Drill small hole in pressure vessel, Use steam deflector
	Dropping	x	Personnel injury	Pretest cables, Institute personnel control measures
	Rupture of one or more heat pipes	x	Personnel injury from potassium vapor	Provide adequate ventilation, Design for guided extraction of heat pipes, Control positioning of upper pressure vessel
	Hot surfaces	x	Personnel injury	Provide active cooling of source-shield assembly, Provide protective clothing
Transportation of heat source-shield			Refer to Table 4-4	
Disassembly of Heat source-shield	Dropping heat block shield	x	Personnel injury	Pretest cables, Institute personnel control, Define idea assembly procedures

TABLE 4-9 (cont'd.)

Phase	Failure Mode	Probability x=possible o=unlikely	Effect	Required Response or Correction
Disassembly of Heat source-shield	Removing welds on shield plugs	x	Radiation	Step plugs to prevent radiation streaming
	Steam	o	Personnel burns	Exercise caution when breaking through weld, Use a steam diverter
	Hot surfaces	x	Personnel injury	Provide cooling and/or personnel guards
Removal of heat sources	Radiological hazard	o	Excessive dose	Use remote disassembly with adequate shielding
	Dropping and delayed recovery	o	Fire hazard	Guarantee immediate recovery Provide heat sink catcher tray
	Heat sink failure	o	Overheating of several capsules	Monitor heat sink condition, Provide standby emergency cooling
	Sources stuck in shield	x	Complicates source removal, Unusual procedures may result in burns or excessive radiation exposure	Have contingency plan for this eventuality

5.0 Safety Analyses

5.1 Normal Mission Evaluation

5.1.1 Radiation Shielding

The radiation shielding of the reference RTG design was calculated by handbook methods (Ref. 1, 2) using gamma ray emission rates from Reference 1. Considerable precision has recently been achieved in shielding calculations through the use of general geometry point-kernel and Monte Carlo computer programs. For calculational purposes the reference design was simplified to the geometry of Figure 5 1. This simplification is equivalent to the reference design with the fins deleted and the corners squared. The radiation dose at the 34 KW (th) power level was calculated using a modification (Ref. 3) of the Modified Point-Kernel Code Quad P5A (Ref. 4). This program uses a Green's function calculation of the penetration with tabulated build-up factors. The cross sections, gamma-ray spectra and source strengths are from the ENDF/B file of evaluated nuclear data. The results of these computer calculations for the 12 locations are given in Table 5-1.

These calculations are believed to be slightly optimistic (high) (Ref. 5). A Monte Carlo code such as Morse or OGRE could be used to more accurately predict the radiation streaming up the heat pipe holes. The results shown in Table 5-1 indicate that the shielding does not completely satisfy the 200 mr/hr. contact criterion of 49 CFR 173.

The allowable whole body dose for radiation workers in restricted areas is 1.25 rem body dose for a calendar quarter (10 CFR 20.101). The dose from the side is about 100 mr/hr. so this limits each worker to about 12.5 hours of exposure per calendar quarter.

The allowable whole body dose for individuals in non-restricted areas (10 CFR 20.105) is 0.5 rem in one calendar year. If it is assumed the RTG is no closer than 50 feet to any living area, the extrapolated dose is 0.5 mr/hr. Overnight exposure would result in a 50 mr exposure, well within the requirements.

The Department of Transportation requires (49 CFR 173.398) that the dose 6 feet from the transport vehicle to be less than 10 mr/hr. Assuming a truck bed width of 10 feet, the extrapolated dose is 10 mr/hr. and meets requirements.

Figure 5.1 RTG Shield Simplified for Analysis (Source circle is 11.3" and heat pipe circle is 21.25"). The numbers indicate detector locations for the point-kernal calculation.

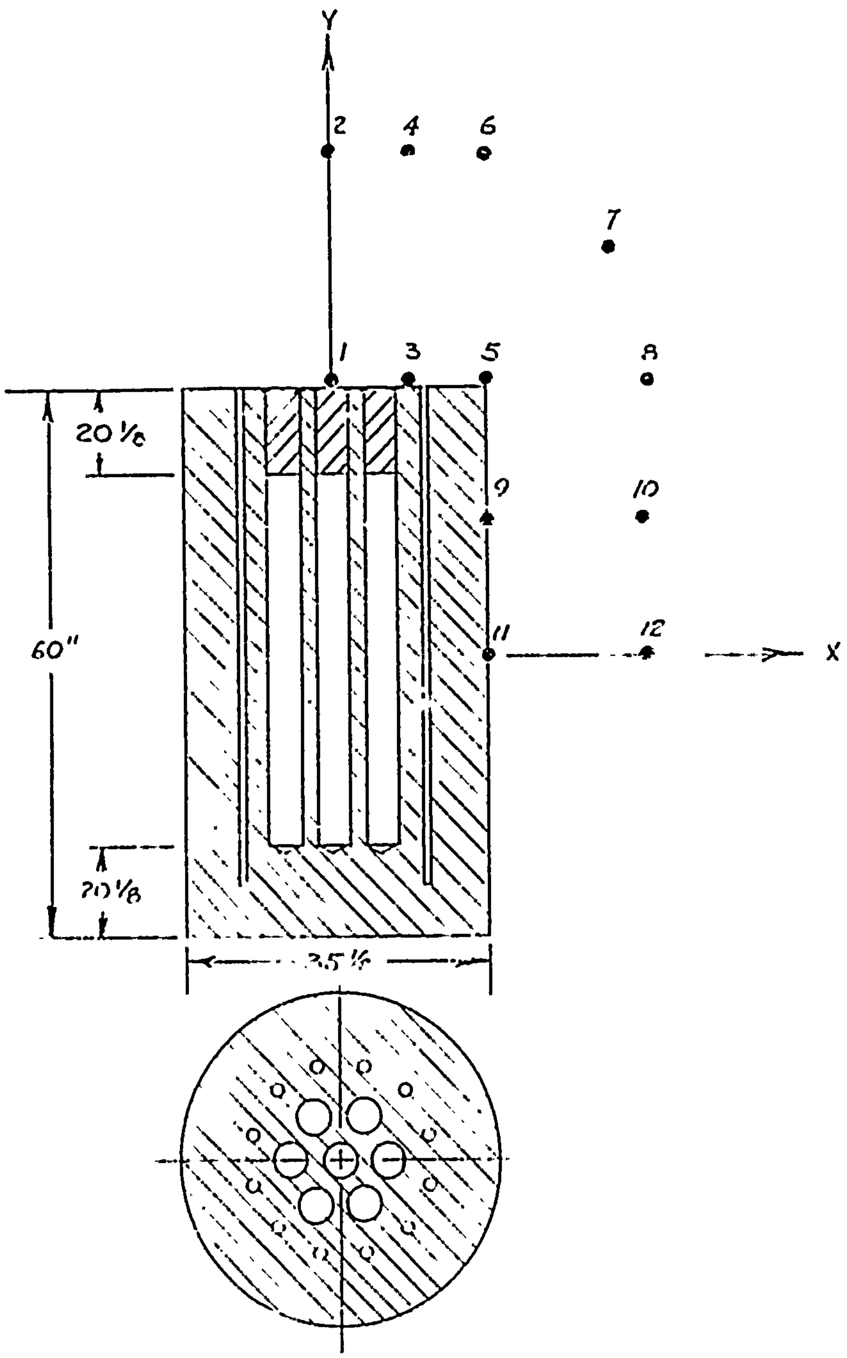


TABLE 5-1

RESULTS OF POINT-KERNEL SHIELDING CALCULATIONS FOR 34 KW (th) RTG

Detector Location Number	Locations Coordinates (cm)		Dose With Heat Pipe Holes Open (mr/hr)	Dose With Heat Pipe Holes Plugged With Steel Rods (mr/hr)
	X	Y		
1	0	153.5	256*	256
2	0	253.5	43	43
3	14.8	153.5	203	203
4	14.8	253.5	40.2	40.2
5	45.2	153.5	0.62	0.58
6	45.2	253.5	20.8	20.8
7	95.2	203.0	0.53	0.2
8	145.2	153.	33.0	17.1
9	45.2	127.8	83.0	82.3
10	145.2	127.8	64.0	33.7
11	45.2	176.5	164.0	164.0
12	145.2	176.5	104.0	55.9

* Exceeds maximum allowable level of 200 mr/hr

In conclusion, the shielding design appears slightly inadequate at the end positions, but satisfactory otherwise. If radiation streaming in the heat pipe holes is found to result in excessive dosages, the heat pipe holes may be plugged temporarily with steel rods.

5.1.2 Heat Effects during Transportation

A detailed thermal analysis is presented in Appendix D. It is found that a temperature of 88°F above ambient will be reached by the mesh guard about the RTG mounted on the carrier. (Guard dimensions: 8 feet diameter, 10 feet high). Therefore, the side of the mesh will not exceed 180°F unless the ambient temperature exceeds 92°F.

The hot air rising from the heat block-shield will reach 310°F and is incompatible with DOT regulations. Some form of baffling to mix in cold air is needed to cool this air before it reaches the top of the guard.

It is found that the RTG resting on a steel carrier will cause the bed, in the region of contact, to exceed DOT requirements. It is suggested that an insulator such as 4 inches of concrete be used as a support base. Then it is found that the carrier bed will not exceed 150°F at the guard boundary.

5.1.3 Seawater Leaks

Leaks may develop from many different causes; damage or imperfections in the pressure vessel seal, the TEM thimble seals or the power feedthrough connection seals. No device is presently included in the design to act as a "getter" i.e., to remove the seawater leakage by chemical or physical means. Any leakage will remain in the system until retrieval and/or disassembly.

In Figure 5.2 the reference RTG is shown with a hypothetical leak in the pressure vessel seal. The seawater jets in, but cannot strike any surface above boiling temperature and thus remains liquid, accumulating in the bottom pressure vessel and impregnating the non-fusible insulation. Eventually the water depth may become great enough that it boils and forms steam.

The available internal volume for steam to occupy, assuming an effective pressure vessel height of 73.6 inches and an internal diameter of 50 inches is 1.45×10^5 cubic inches.

The volume of the heat block-shield is 5.93×10^4 cubic inches. The fusible aluminum insulation has a density of 0.0596 lb/cu.in. (Ref. 6) and hence a void fraction 0.02. The density

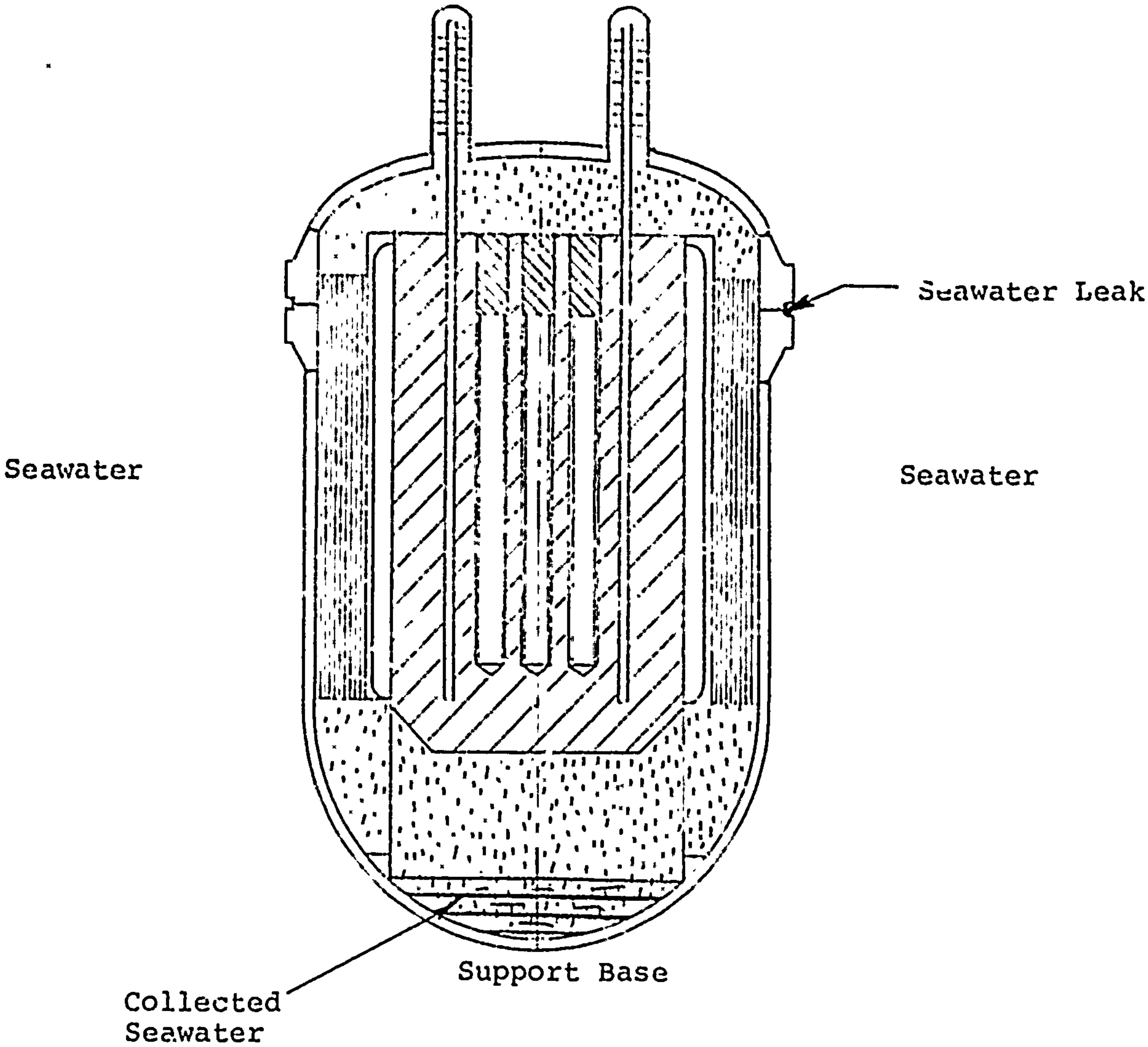


Figure 5.2 Hypothetical Small Seawater Leak

of the non-fusible insulation is assumed to be 0.28 lb./cu.in. with a void fraction of 0.08. The aluminum fusible insulation volume is 4.88×10^4 cubic inches and the non-fusible insulation volume is 3.69×10^4 cubic inches giving a total empty volume of 8.18×10^4 cubic inches that can be filled with steam.

The thin walled (.083 in.) heat pipes were examined for susceptibility to high pressure failure. Roark (Ref. 7) determined the critical pressure for a long tube as:

$$p = \frac{1}{4} \frac{E}{1-\nu} \frac{t^3}{r^3} \qquad (5.1)$$

Where E = modulus of elasticity (27×10^6 lb./in.^{2})

ν = Poisson's ratio (.3)

t = wall thickness (.083 in.)

r = radius (.5 in.)

This relationship gives a critical pressure of 44,000 psi. A 100% safety factor reduces the critical pressure to about 22,000 lb./in.^{2}. This value is well in excess of the pressure that the system would experience at 20,000 feet.

If it is assumed that the steam does not significantly depress the temperature of the heat block-shield from the normal operating surface temperature (1360^{o}F).

The quantity of steam needed to fill the available volume inside the RTG is:

$$L_H = \frac{L_W \times \Delta P_H}{\Delta P_W} \frac{M_W}{T_W} \frac{T_H}{M_H} \qquad (5.2)$$

Where P_W is the water pressure at 20,000 feet depth (10,000 lb/in.^{2})

P_H is the helium differential pressure - 14.7 lb/in.^{2}

M_H is the molecular weight of helium (2)

T_H is the helium temperature (80^{o}F)

M_W is the molecular weight of water (18)

T_W is the water temperature (0^{o}F)

L_H is the helium leak rate

This gives a scaled helium leak rate of 0.13 gm/year. In terms of volume, this is a helium leak rate of 1.45 liters/year or 4.6×10^{-5} std. cc/sec. Modern helium leak detectors are capable of detecting leaks in the range 10^{-3} to 10^{-10} std. cc/sec. (Ref. 9). When leak rates are less than 10^{-8} std.cc/sec. the water molecules are too large to fit through the opening (Ref. 9), although helium leaks can still be detected.

It is believed that the maximum leak criterion of 4.6×10^{-5} std.cc/sec is conservative because:(1) some water inside of the pressure vessel will remain liquid on the bottom in contact with the cold pressure vessel wall and protected from the heat of the source-shield by the bottom insulation, (2) the steam will not form uniformly at the temperature of the source-shield but will be subjected to a temperature gradient due to the lower temperature of the pressure vessel wall, (3) the steam will tend to reduce the source-shield temperature through increased convection and possibly a heat piping effect.

If a slow leak should result in failure of the heat pipes, the fusible insulation will melt. Figure 5.3 is a graph of the fraction of the total power carried by radiant heat flux as a function of the melted insulation area. Tests were performed with the fusible shield that demonstrated its effectiveness (Ref. 10). Melting assures shield removal by gravity from the melted area.

An investigation was conducted into the possibility of reacting the aluminum to form a ceramic Al_2O_3 insulation which would resist melting and removal under overheating conditions. To form this ceramic insulation in situ without changing the physical form (crumbling) is not regarded as credible. If the oxidized insulation does crumble, it will pass radiant heat flux to the outside and prevent overheating as effectively as melting.

A reaction of the aluminum screening with chloride ions in the leaked seawater is another possibility. This reaction readily forms aluminum chlorate or chloride which would simply either dissolve in water or melt below 400°F, allowing radiant heat flow to the outside in either case.

If water does leak into the RTG and causes the fusible aluminum insulation to dissolve or melt, the remaining barriers preventing dispersion of the fuel in the ocean are: (1) the ceramic nature of the fuel, (2) the 0.32 inch thick encapsulation of the fuel, (3) the heat source-shield having a minimum thickness of 2.4 in. from fuel well to heat pipe well and 6.63 in. directly to the outside and (4) the pressure vessel.

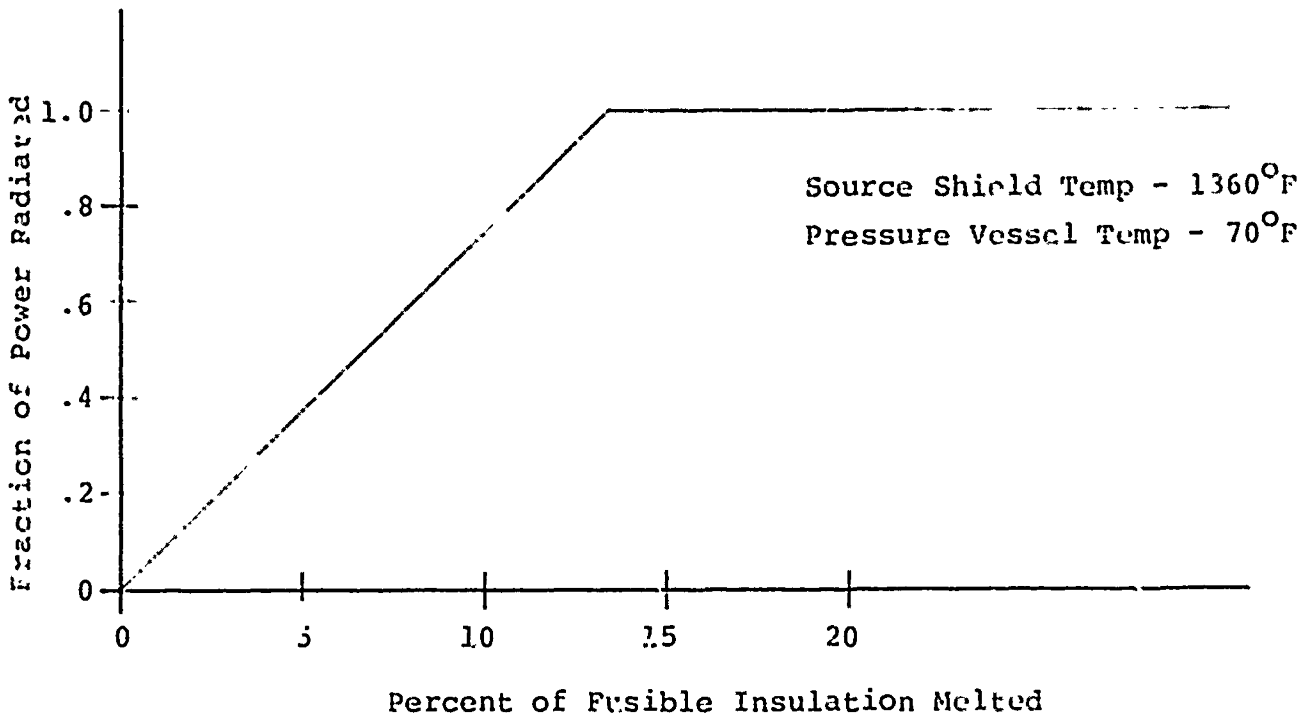


FIGURE 5.3. Percentage of Fusible Insulation Required to Melt to Radiate 34 KW

5.1.4 Sedimentation - Effect on Heat Transfer

Figure 3.6 indicates that the dimensions of the TEM assembly and pressure envelope will be approximately 10 in. high by 4.5 in. diameter. For the 12 thimbles, the heat flux is .215 KW/sq.in. or 1.06×10^5 BTU/hr-sq.ft.

Convective heat flow is expressed as

$$\frac{Q}{A} = \frac{K\Delta T}{\delta} \qquad (5.3)$$

Where K is the thermal conductivity of water (.33 BTU/hr.-ft.-°F)
T is the temperature driving the convection (43°F)
δ is the boundary layer thickness

Evaluating equation 5.3, δ is found to be 1.61 mils.

The reference sedimenta n rate is .02 inches per ten years. If this sediment could adhere o the vertical surface of the thimbles thereby increasing the boundary layer by this amount the TEM cold shoe temperature will rise to 460°F. However, it is unlikely that a sediment layer thicker than the grain size of sediment could accumulate on the vertical surfaces of the TEM thimbles. Demars and Anderson (Ref. 28) indicate that only clays and silts are found away from the continental shelf. The average size of these silt particles is about 0.4 mils. This addition to the boundary layer would increase the TEM temperature to 83°F (from the design basis 75°F). There does not appear to be any way that this sedimentation rate can cause a safety hazard or significantly degrade performance.

5.1.5 Sea Currents

The RTG will be held to the seabed foundation by gravity. It will be constrained from sliding off the foundation. Sea currents could conceivably topple the RTG from the foundation.

The drag force per unit RTG height was calculated as:

$$F = \frac{C_D A \rho V^2}{2} \qquad (5.4)$$

Where A is the area per unit height (4.62 sq. ft./ft.)
ρ is the density of water (64 lb./cu.ft.)
C_D is the drag coefficient (0.3 for very large Reynolds numbers)

In addition to the drag force, the RTG may not be on a level sea bottom. Using a width of 55.5 in., a height of 82 in. and assuming the center of gravity is at 41 in., the critical tipping angle in still water was found to be 34.1°.

If it is conservatively assumed that the water current is flowing in the direction in which the RTG is leaning, the gravity and drag force components are additive. Figure 5.4 presents the combination of seabed slope and water currents necessary to topple the RTG from its foundation.

5.2 Accident Evaluations

5.2.1 Transportation Accident

5.2.1.1 Comparative Risk

The shipment of the source-shield assembly (SSA) presents less risk to the public and environment than the shipment of an equivalent amount of spent reactor fuel, a subject that has received extensive analysis. This is based primarily on the comparative non-dispersibility of the Sr_2TiO_4 as compared with the fission products contained within spent fuel elements. The activity of the RTG at 5 MCi compares with 2.3 to 16 MCi for spent fuel shipments (Ref. 11). The heat generation of the RTG fuel at 34 KW compares with 10 to 70 KW for spent reactor fuel shipments (Ref. 11).

The environmental impact due to the normal transportation of these spent fuel casks has been carefully analyzed for truck, rail and barge transportation. Table 5-2 adapted from this reference shows the relative distribution of these modes of travel. The Table has been normalized using 9000 MW (e) as the present reactor power capability of the U.S. Assuming that the SSA is equivalent to the shipment of 1.7 metric tons of spent fuel that has cooled for 150 days (based on heat output) Table 5-3 of Ref. 12 can be modified to provide an upper bound of the radiation impact presented to people involved in the shipment. To put this in perspective, the dose to the population from natural background is about 78000 man-rem/year (Ref. 12). Clearly, the shipment of the SSA under normal conditions presents negligible environmental risk.

5.2.1.2 Probability of a Transportation Accident

The probability of a severe transportation accident that could result in a radiological impact on the environment has been considered by the NRC (Ref. 12), by Brobst (Ref. 13), Yadigaroglu *et al* (Ref. 14) and Garrick *et al* (Ref. 15). The

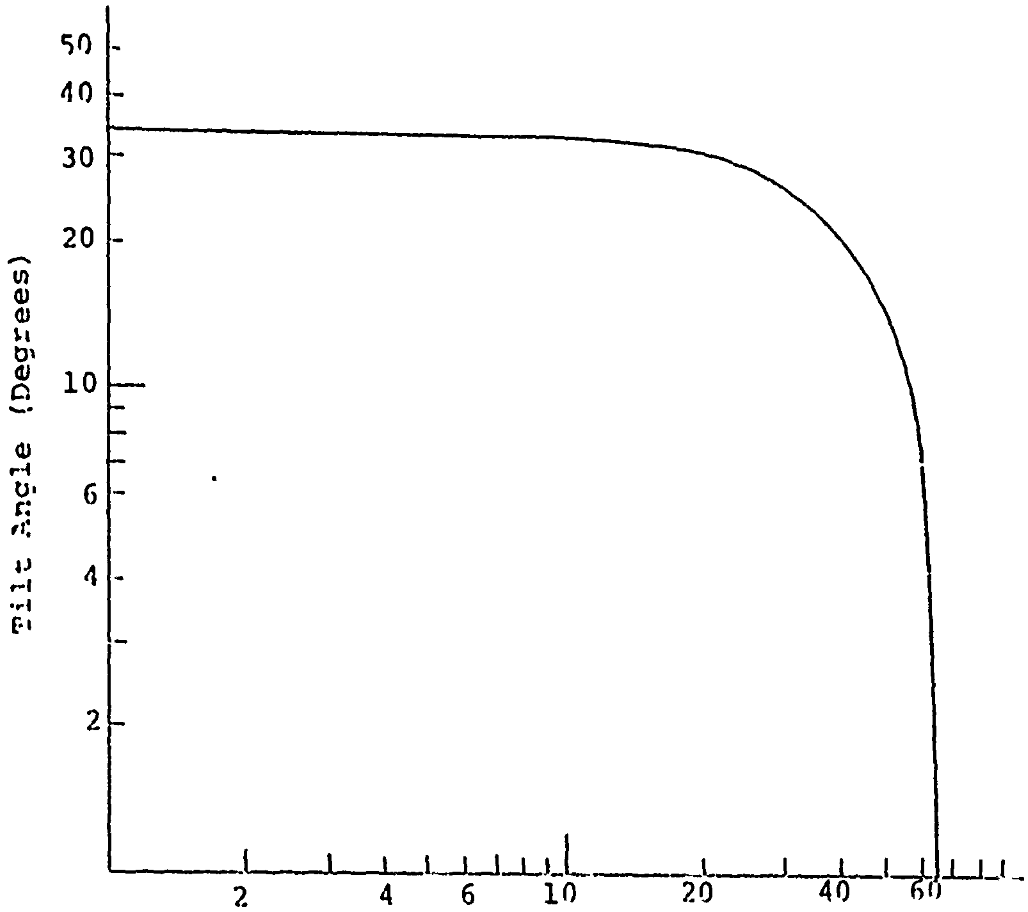


Figure 5.4 Combinations of Sea Current and Sea Bed Tilt which Could Topple the RTG from its Foundation (RTG weight - 25,000 lb.)

TABLE 5-2

SUMMARY OF INFORMATION ON SHIPMENTS

Type of Shipment	Mode of Transport	Average Shipment	Heat Generated By Shipment (kilowatts)	Number of Shipments Per Year	Estimated Average Shipping Distance (miles)	Total Shipping Distance Per Reactor Year (miles)
Irradiated Fuel	Truck	35	10	480	1,000	480,000
	Rail	100	70	82	1,000	82,000
	Barge	135	140	41	1,000	41,000

TABLE 5-3

BOUNDING RADIATION DOSES FOR NORMAL CONDITIONS OF 1000 MILE TRANSPORT OF SOURCE-SHIELD ASSEMBLY (ASSUMING EQUIVALENCE TO 1.7 TONS OF 150 DAY REACTOR FUEL)

	TRUCK		RAIL		BARGE	
	Man-rem	No. People	Man-rem	No. People	Man-rem	No. People
Transport Workers	0.068	4	0.0028 (0.15)	100 (22)	0.0023	10
General Public-Onlookers	0.045	600	0.0056	100	-	-
People Along The Route	0.056	3×10^5	0.011	3×10^5	0.0017	1×10^5

pertinent results of their work are summarized here. Details are available in the Reference documents.

The thirty foot drop test required separately for the fuel capsules is roughly equivalent to a 60 mph collision (Ref. 13). This is justified by the fact that the 30 foot drop is onto an unyielding surface while in a normal truck or train collision, there is considerable material to be crushed before the shipping container comes to rest.

Another potentially severe transportation accident is fire. Truck accident data (Ref. 16) indicate that fire is involved in about 0.8% of all truck-truck collisions, 0.3% of truck-auto collisions, 0.6% of truck-fixed object collisions, 2% of truck-train collisions, and 1% of roll-over/run-off accidents. Most fires involve only the fuel from the vehicle fuel tanks and last less than ½ hour, unless a combustible freight becomes involved. Only in the case of truck-truck collisions is there likely to be a larger supply of fuel involved (e.g., a gasoline tank truck). Some fires have started from overheated tires or accidental ignition of cargo. Truck-auto, truck-bus, and single vehicle accidents are considered to be essentially free of fires lasting longer than ½ hour, (Ref. 17) and then only when one of the trucks is carrying significant amounts of flammable cargo (e.g., tank trucks with gasoline or liquefied petroleum gas, van trailers carrying barrels of paint, etc.). It is conservatively assumed that at least one of the trucks in each truck-truck accident is carrying flammable cargo. Of all truck accidents, 15.5% involve other trucks. This is therefore, the maximum percentage of truck collisions having a potential for long fires.

Of the fires which do occur, it has been estimated (Ref. 18) that 1% of the fires last more than one hour, 10% last between ½ hour and one hour and the balance, 89%, last less than ½ hour. Although there are fires in transport which last for several days, in most cases these involve the burning of only small amounts of fuel per unit time, and are of little consequence in terms of heat output or temperature.

Using these criteria, the NRC assumes the following accident severity categories:

TABLE 5-4

TRANSPORTATION ACCIDENT SEVERITY

Transportation Accident Severity Category		Vehicle Speed at Impact (mph)	Fire Duration (hr)
1.	Minor	0 - 30	0 - ½
		30 - 50	0
2.	Moderate	0 - 30	½ - 1
		30 - 70	<½
3.	Severe	0 - 50	>1
		30 - 70	½ - 1
		>70	0 - ½
4.	Extra Severe	50 - 70	>1
		>70	½ - 1
5.	Extreme	>70	>1

Combining these categories with truck, train and barge statistics, the following accident probabilities are found (Table 5-5).

To an order of magnitude, the accident probabilities for the different modes of transportation are the same and are summarized in Table 5-6.

TABLE 5-5

APPROXIMATE ACCIDENT PROBABILITIES FOR TRUCK, RAIL AND BARGE PER VEHICLE MILE FOR THE ACCIDENT SEVERITY CATEGORIES

Minor	Moderate	Severe	Extra Severe	Extreme
2×10^{-6}	3×10^{-7}	8×10^{-9}	2×10^{-11}	1×10^{-13}

TABLE 5-6

ACCIDENT PROBABILITY

Severity Category	Vehicle Speed (mph)	Fire Duration (hr)	Probability Per Vehicle Mile		
			Rail	Truck	Barge*
Minor					
	0 - 30	<½	6×10^{-9}	6×10^{-9}	--
	0 - 30	0	4.7×10^{-7}	4×10^{-7}	1.6×10^{-6}
	30 - 50	0	2.6×10^{-7}	9×10^{-7}	1.4×10^{-7}
Total			7.3×10^{-7}	1.3×10^{-6}	1.7×10^{-6}
Moderate					
	0 - 30	½ - 1	9.3×10^{-10}	5×10^{-11}	--
	30 - 50	<½	3.3×10^{-9}	1×10^{-8}	8×10^{-9}
	50 - 70	<½	9.9×10^{-10}	5×10^{-9}	2×10^{-9}
	50 - 70	0	7.5×10^{-8}	3×10^{-7}	3.4×10^{-8}
Total			7.9×10^{-8}	3×10^{-7}	4.4×10^{-8}
Severe					
	0 - 30	>1	7.0×10^{-11}	5×10^{-12}	--
	30 - 50	>1	3.9×10^{-11}	1×10^{-11}	9.3×10^{-11}
	30 - 50	½ - 1	5.1×10^{-10}	1×10^{-10}	1.3×10^{-9}
	50 - 70	½ - 1	1.5×10^{-10}	6×10^{-12}	3.3×10^{-10}
	>70	<½	1×10^{-11}	1×10^{-10}	--
	>70	0	8×10^{-10}	8×10^{-9}	--
Total			1.5×10^{-9}	8×10^{-9}	1.6×10^{-9}

TABLE 5-6 (continued)

ACCIDENT PROBABILITY

Severity Category	Vehicle Speed (mph)	Fire Duration (hr)	Probability Per Vehicle Mile		
			Rail	Truck	Barge*
Extra Severe	50 - 70	>1	$1.1x10^{-11}$	$6 \; x10^{-13}$	$2.3x10^{-11}$
	>70	½ - 1	$1.6x10^{-12}$	$2 \; x10^{-13}$	--
Total			$1.3x10^{-11}$	$8 \; x10^{-13}$	$2.3x10^{-11}$
Extreme	>70	>1	$1.2x10^{-13}$	$2 \; x10^{-14}$	--
Total			$1.2x10^{-13}$	$2 \; x10^{-14}$	--

*Barge accident probabilities are based on the duration of the fire and actuarial data on cargo damage. The impact velocities of all barge accidents were considered to be less than 10 mph, but for the purposes of this table, minor cargo damage is assumed to be equivalent to vehicle impact speeds of 0 - 30, moderate cargo damage 30 - 50 and severe cargo damage 50 - 70.

Considering that only extra severe to extreme accidents could have a damaging effect on the SSA and that the mean trip distance is 1000 miles, the estimated probability of a dangerous transportation accident is 2×10^{-8}. Table 5-7 is presented to put this risk in perspective with accepted risks of greater consequence. (Ref. 19).

5.2.1.3 Consequence Analyses

5.2.1.3.1 Fire

Severe transportation fires, including the cargo, seldom last more than a half hour except in ships and storage depots (Ref. 21), because either the fuel is exhausted or the fire is extinguished by fire-fighting crews. Although flame temperatures of liquids, such as jet fuel or kerosene, may reach 1,800° - 2,000°F, such peak temperatures are reached only very locally near the surface of the material involved in the fire. Only under very unusual circumstances is more than 50 percent of a package surface likely to be exposed to the flame for as long as a half hour. Even in a longer fire, the package may be in a location where the fire will have little or no effect on it (Ref. 20).

Nevertheless, the behavior of the source-shield assembly in a fire of 1475°F and 1850°F is investigated. The 1475°F fire represents the hypothetical accident environment specified by the NRC (Ref. 19), DOT (Ref. 21) and IAEA (Ref. 22). Surviving this fire environment implies that the RTG can meet nominal transport requirements for thermal environments.

The surface temperature of the source-shield assembly in a 100°F ambient environment assuming only radiative cooling is 622°F. Extrapolating this to an environment of 1475°F yields an equilibrium surface temperature of 1521°F.

The 1850°F half-hour fire was used in the SNAP-23A preliminary safety analysis as representative of a severe petroleum conflagration. The equilibrium surface temperature of the RTG in this environment would be 1877°F.

In neither of these fires do temperatures reach levels sufficient to cause an environmental hazard. These temperatures are well below the melting points of the fuel encapsulation (2450° to 2500°F) or the heat block-shield (2720°F) or the phase transitions in the Sr_2TiO_4 fuel at 2620° and 2980°F.

There is no anticipation of an environmental release of radioactive materials due to immersion in credible transportation fires.

TABLE 5-7

INDIVIDUAL RISK OF ACUTE FATALITY BY VARIOUS CAUSES
(U.S. Population Average 1969)

Accident Type	Total Number For 1969	Approximate Individual Risk Acute Fatality Probability/Yr.(a)
Motor Vehicle	55,791	3×10^{-4}
Falls	17,827	9×10^{-5}
Fires and Hot Substance	7,451	4×10^{-5}
Drowning	6,181	3×10^{-5}
Poison	4,516	2×10^{-5}
Firearms	2,309	1×10^{-5}
Machinery (1968)	2,054	1×10^{-5}
Water Transport	1,743	9×10^{-6}
Air Travel	1,778	9×10^{-6}
Falling Objects	1,271	6×10^{-6}
Electrocution	1,148	6×10^{-6}
Railway	884	4×10^{-6}
Lightning	160	5×10^{-7}
Tornadoes	91(b)	4×10^{-7}
Hurricanes	93(c)	4×10^{-7}
All Others	8,695	4×10^{-5}
All Accidents		6×10^{-4}
Nuclear Accidents (100 reactors)	0	3×10^{-9}

(a) Based on total U.S. population, except as noted.
(b) (1953-1971 average)
(c) (1901-1972 average)

5.2.1.3.2 Explosion

It was shown in Section 5.2.1.2 that the probability of vehicle-vehicle collisions is very remote and that the probability of collision between the RTG carrier and a truck carrying a large amount of explosive fuel is even more remote. Nevertheless, several years ago, a truck carrying 9000 gallons of propane (the maximum allowable) skidded, overturned, ruptured and exploded. It is conceivable that such a truck could collide with the RTG carrier and explode.

Such an accident was analyzed in the Preliminary Safety Analysis Report for the SNAP 23-A (Ref. 23). Assuming a 2% propane TNT equivalence, the maximum reflected overpressure at 30 feet, from the explosion is 330 psia. This report finds that to produce a 10% deformation in an Inconel-625 shield 24 inches diameter, 13 in. high and 0.053 inches thick, requires a shock pressure of 6030 psia.

Because this thin shell would withstand this hypothetical explosion, there is no reason to believe the heat block-shield having a 5.08 inch steel minimum wall thickness and further strengthened by a 1.5 inch minimum webbing thickness would suffer damage to the extent of releasing radioactive material.

5.2.1.3.3 Water Submersion During Transportation

The NRC/DOT Requirements specify that the fuel must maintain its integrity for 24 hours in pH(6-8) water at room temperature. The complete submersion of the SSA in water would not produce any effects other than heating the water and cooling the SSA. It is assumed that such an accident would be known about immediately. The time of submersion will be controlled by the time required to procure and operate a crane to remove the RTG from the water. Arrangements should be made in advance of transport to locate suitable cranes and operators along the route.

5.2.1.3.4 Partial Burial in Dry Sand

The SSA was tested for burial in dry sand as reported in reference 16. Approximately 60% of the shield was covered by sand. The heat sources were simulated by electrical heaters supplying up to 33 KW. The maximum SSA temperature measured was 1,150°F near the heat sources. Since the fuel elements are qualified to 2000°F, this accident environment does not represent a nuclear safety hazard.

5.2.2 Natural Occurrences During Normal Operation

5.2.2.1 Earthquakes

Earthquakes occur somewhere in the earth on the average of every few minutes. Most are minor shocks of little engineering significance. Severe earthquakes may have safety implications for the RTG due to:

1. Heat Pipe damage due to vibration
2. Bearing capacity failure of the seabed sediment
3. RTG tip-over due to gross horizontal or vertical displacements
4. RTG burial by slope failure at or adjacent to the site
5. RTG burial or tip-over by turbidity currents

The internal structures of the RTG are supported by short rigid members closely packed with insulation. An earthquake could cause system responses which excite the pressure vessel out of phase with the heat block-shield to such a degree that the heat pipes could be broken. The nonfusible and fusible insulation should provide some support and damping, but the radiator fins on the heat block will tend to dig into the fusible insulation and reduce the effectiveness of this support. Some form of lateral rigid connection between the heat block and the pressure vessel is clearly required.

A severe earthquake may topple the RTG from its seabed foundation. If the RTG should topple, it may fall on the TEM thimbles and cause failure of the pressure vessel. This would cause mission failure, but it is very unlikely to have an environmental impact. The remaining redundant barriers are provided by: (1) diffusion through the crack in the pressure vessel, (2) the heat block-shield, and (3) the encapsulation of the fuel itself.

This toppling criteria does afford a measure of the severity of an earthquake necessary to have performance significance. The angle formed by the center of gravity to the support point (assumed to be at the RTG diameter 55.5 inches) is 81.5°. The minimum horizontal acceleration necessary to achieve tip-off from the foundation is 0.68 g. Whether or not the RTG reaches the critical tilt angle of 99.5° depends on the frequency spectrum, the vertical acceleration and the horizontal displace-

ment. Appendix E presents an analysis that establishes a 1.0 g horizontal acceleration as a toppling criterion.

The NRC (Ref. 24) provides a design basis response spectrum based on the recorded ground accelerations and response spectra of past earthquakes. The Design Response Spectra specified for design purposes can be developed statistically from measurements of past strong-motion earthquakes (Ref. 25). An extensive study has been described by Newmark and Blume (Ref. 25, 26 & 27). After reviewing these referenced documents, the NRC Regulatory Staff determined the following procedure acceptable for defining the Design Response Spectra representing the effects of the vibratory motion of the SSE and the Operating Basis Earthquake (OBE) on sites underlain by either rock or soil deposits covering all frequencies of interest. However, for unusually soft sites, modification to this procedure will be required.

In this procedure, the configurations of the horizontal component Design Response Spectra for each of the two mutually perpendicular horizontal axes are developed. These shapes agree with those developed by Newmark, Blume and Kapur (Ref. 25). The Base Diagram (Fig. 5.5) consists of three parts: the bottom line on the left part represents the maximum ground displacement, the bottom line on the right part represents the maximum velocity. The horizontal component Design Response Spectra corresponds to a maximum ground displacement assumed proportional to the maximum ground acceleration which is set at 36 inches for a ground acceleration of 1.0 g.

The conditions of 1.0 g acceleration and 36 inch displacement could topple the RTG from its foundations. The force causing the tilt of the RTG is an inertial force and it is not clear from the frequency response spectrum of Fig. 5.5 that the imposed earthquake frequencies are high enough to cause the RTG to tilt past the critical angle. The problem is non-linear even considering only the horizontal motion and much more complex when the vertical motion is introduced (see Appendix E).

It is apparent that an earthquake having at least 1.0 g horizontal acceleration is approximately of the magnitude necessary to topple the RTG.

The probability that such a phenomenon will occur requires that this acceleration criterion be converted to the Richter Scale in which earthquakes are usually measured.

Figure 3 of Demars and Anderson (Ref. 28) presents maximum ground acceleration as a function of distance from the epicenter and the earthquake magnitude on the Richter Scale. The curve for acceleration directly above the fault can be fit by the equation:

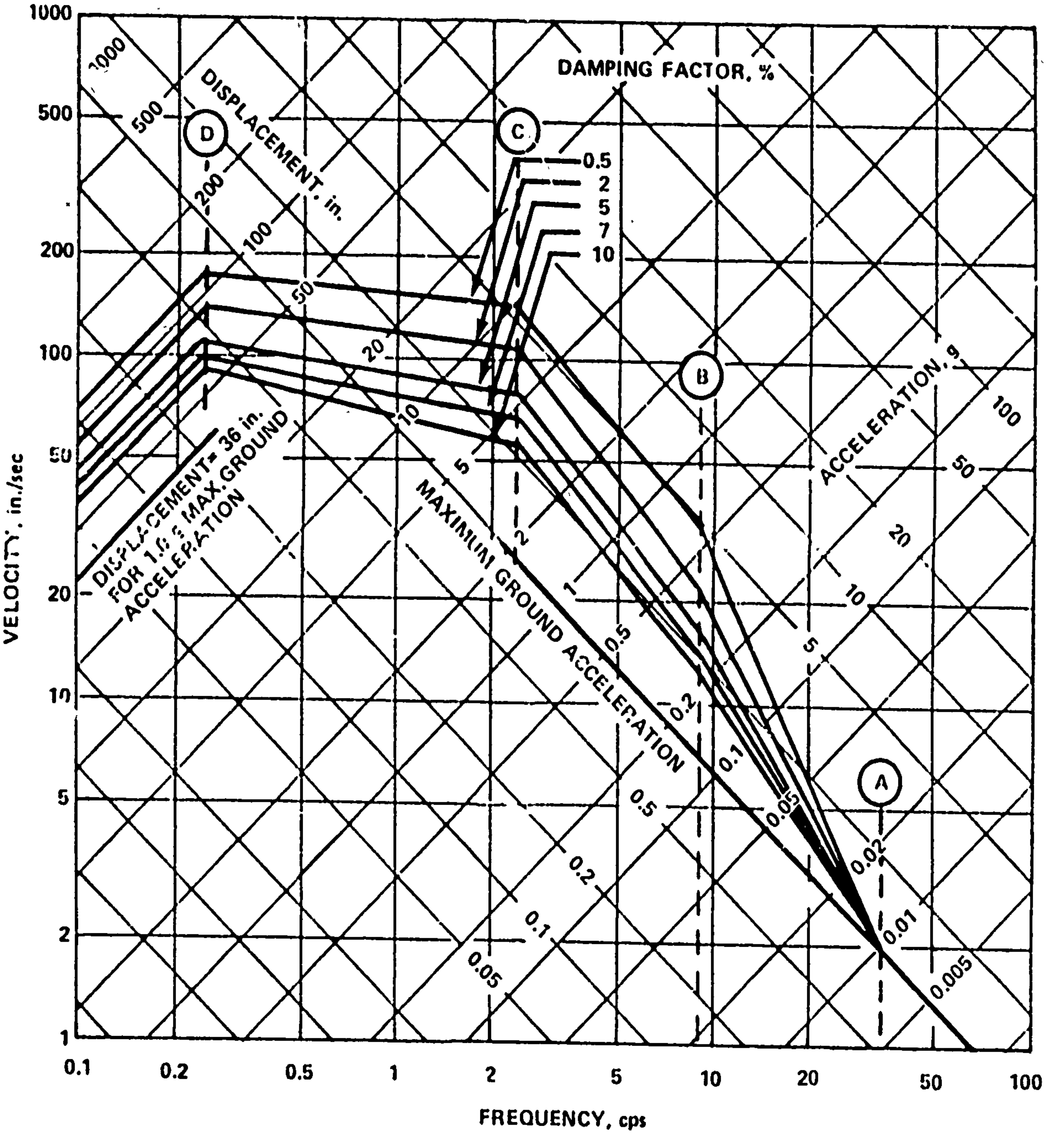


Fig. 5.5 Horizontal Design Response Spectra - Scaled to 1g Horizontal Ground Acceleration.

$$a = 0.095M - 0.3 \qquad (5.5)$$

where a is the acceleration in fractions of g and M is the earthquake magnitude on the Richter Scale.

Equation 5.5 predicts that the Richter value for the earthquake with a 1.0 g acceleration at the epicenter is 13.7. This is a minimum value. If the RTG is located away from the epicenter, the required Richter value is much higher.

Gutenberg and Richter (Ref. 29) found that the mean annual frequency N of shallow focus earthquakes with magnitude M could be modeled as:

$$\log_{10}N - a + b\ (8-M) \qquad (5.6)$$

for the world as an average, Gutenberg and Richter give:

$a = 0.48$ and $b = 0.9$ from which $N = 1.6 \times 10^{-6}$ years.

This number should be taken as very approximate since a linear extrapolation was assumed to estimate the Richter value corresponding to a 1.0 g acceleration. There have been no earthquakes recorded at that level. The most valid conclusion to be drawn is that such an earthquake is a very improbable occurrence any place on earth. To occur close to the RTG is even more improbable. Siting away from known areas of earthquake activity would make the situation so rare as to be negligible. Proper engineering design of the foundation support legs to prevent collapse and internal bracing of the RTG to protect the heat pipes should insure RTG operation even after a severe earthquake.

5.2.2.2 Turbidity Currents

Sands and silts eroded from land masses accumulate on the continental shelves and abyssal plains. After sufficient accumulation combined with an initiating trigger, (often a minor earthquake) a portion of the accumulation begins to flow as a dense slurry. This submarine avalanche, called a turbidity current, is responsible for the formation of submarine canyons and the transport of terrigenous sands and organic matter hundreds of miles into the ocean deeps. Heezen and Ewing (Ref. 30) report turbidity currents up to 50 mph. Such a flow rate, coupled with high density of the slurry could topple the RTG from its foundation (Section 4.1.5) or result in silting grossly in excess of that calculated in Section 4.1.4.

The formation of submarine canyons has long been a controversy to oceanographers. One early hypothesis held that the submarine canyons were formed by actual rivers during the ice ages when the oceans were much lower than now and major portions of the continental shelves stood above sea level This theory demands that an incredible amount of flowing water existed in thepast. The turbidity current theory assumes that flows of dense, silt-laden material are continuously forming submarine canyons. This latter theory received considerable support from the voyage of the research vessel Atlantis in 1949 that traced the Hudson River submarine channel for 200 miles from the edge of the continental shelf into the western Atlantic Plain. Core samples taken during the voyage showed that the canyon had been eroded by clays many millions of years old and that the canyon contained not only sand and gravel but shallow water clam shells overlain with a recently deposited ooze (Ref. 31, 32.)

The instability of submarine valley walls has been deduced from commercial telephone cable breakages first pointed out by Milne (Ref. 33). In one case, cable companies have been unable to maintain communications across the canyon head from the mouth of the Congo River. Heezen and Ewing (Ref. 30) used the rate of cable breakage as a measure of the flow rate of the turbidity current that resulted from the 1929 Grand Banks Earthquake. By examining telephone records on the times of cable failure, they found that cables within 60 miles of the epicenter broke immediately, cables continued breaking for more than 13 hours after the earthquake. Each break was down slope from theone before and the last one occurred 300 miles from the epicenter. By knowing break times and distances between breaks, a maximum current speed of 50 mph in the canyon and 15 mph on the plain was calculated. Considerable difficulty was encountered repairing the breaks because of cable burial. About 200 miles of cable had to be replaced. Apparently, flow can be maintained on slopes as gentle as 1:1000 (Ref. 34).

The theory of high speed turbidity current flow is not as well documented as it would seem. Shepard (Ref. 35) suggests that flows of 50 mph over a breadth of 100 miles should carry an enormous amount of sediment; much of it very coarse (Ref. 36). However, conspicuously fine sediments (30-130 microns) were collected in exactly the area where the current was supposed to have moved at the maximum speed. It is possible that the cable breakage interpreted by Heezen and Ewing (Ref. 30) to be due to the long flow path was actually the result of local landslides (falling in from the sides). The only directly observed turbidity current speeds have been in lakes (Ref. 37) and they have been very slow.

With regard to the safety of the RTG, turbidity currents are fairly localized phenomena and can be avoided by proper siting. Figure 5.6 (Ref. 32) shows known turbidity flows as well as areas topographically inaccessible to turbidity currents. Should the RTG be sited such that a severe turbidity current is experienced during the operational history, it is doubtful that currents sufficient to topple it will be experienced at the reference depth (20,000 feet). From examination of seabed samples, it will be possible to determine whether a site has a history of turbidity currents and suitable alternative sites may be selected.

5.2.3 Pressure Vessel Failure

The most likely form of pressure vessel failure is the slow leak. The failure of power plant pressure vessels is an intensively studied subject. There is some evidence that catastrophic failures do not normally occur; intentional test cracks propogated only to a limited extent. Recently an in-depth analysis of actual pressure vessel failures has been performed (Ref. 38). One conclusion of this study is that the probability of disruptive failure of a nuclear reactor pressure vessel is between 10^{-6} and 10^{-7}/year with a confidence limit of 99%.

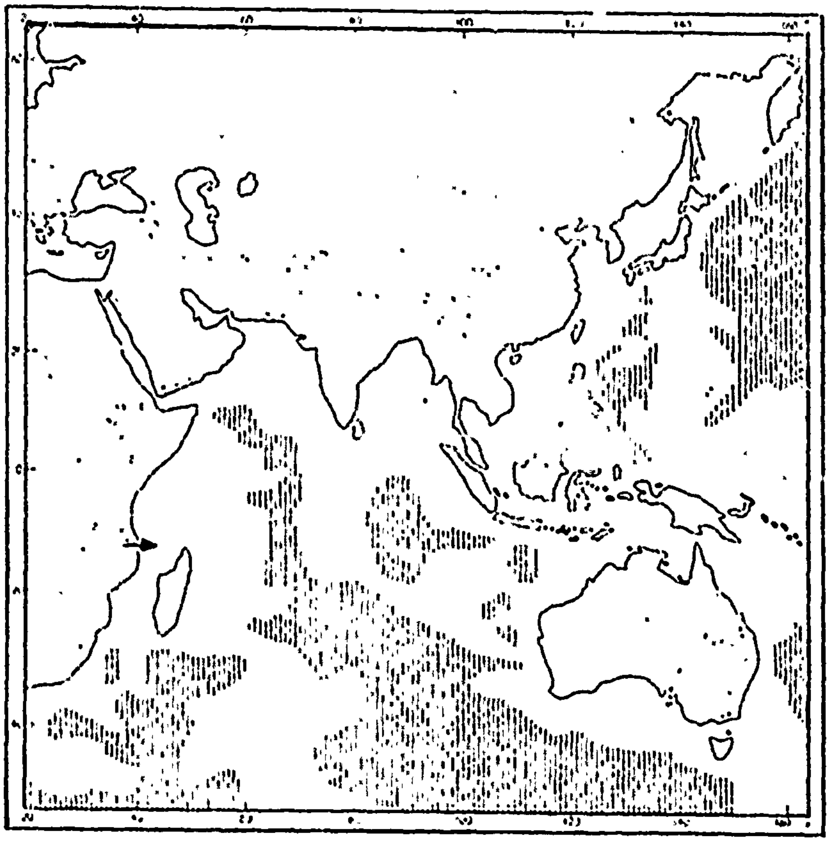
The RTG pressure vessel is primarily under compression. Any catastrophic failure would normally result from elastic instability (buckling) of the sidewalls. It does not appear that this is a credible situation for a properly sized vessel.

Nevertheless, for purposes of accident analysis, it is assumed that an instantaneous gross failure does occur and that the sea rushes in. The heat block-shield surface temperature is abruptly cooled from about 1000°F to 32°F. (This sudden quenching is also a conservative assumption since undoubtedly there would be substantial Leidenfrost formation which would greatly slow the heat transfer rate). The problem of quenching an infinite cylinder is treated analytically in Timoshenko and Goodier (Ref. 39). They find the stress components:

$$\sigma_r = \frac{2\alpha E\ T_o}{1-\nu} \sum_{n=1}^{\infty} e^{-P_n t} \frac{1}{\beta_n^2} - \frac{1}{\beta_n^2} \frac{b}{r} \frac{J_1\ (\beta_n r/b)}{J_1\ (\beta_n)} \tag{5.7}$$

$$\sigma_\theta = \frac{2\alpha E\ T_o}{1-\nu} \sum_{n=1}^{\infty} e^{-P_n t} \frac{1}{\beta_n^2} + \frac{1}{\beta_n^2} \frac{b}{r} \frac{J_1\ (\beta_n r/b)}{J_1 (\beta_n)} - \frac{J_o(\beta_n r/b)}{\beta_n J_1 (\beta_n)} \tag{5.8}$$

$$\sigma_z = \frac{2\alpha E\ T_o}{1-\nu} \sum_{n=1}^{\infty} e^{-P_n t} \frac{2}{\beta_n^2} - \frac{J_o(\beta_n r/b)}{\beta_n J_1 (\beta_n)} \tag{5.9}$$



Historical Turbidity Currents appear as arrows on this map of the oceans of the world The shaded areas represent regions which are inaccessible to turbidity currents coming fro shallow water. The height of these regions and the surrounding topography cut them off from the flows which have taken sand and marine organisms from the continental shelves and transported them to many of the deepest parts of the ocean floor.

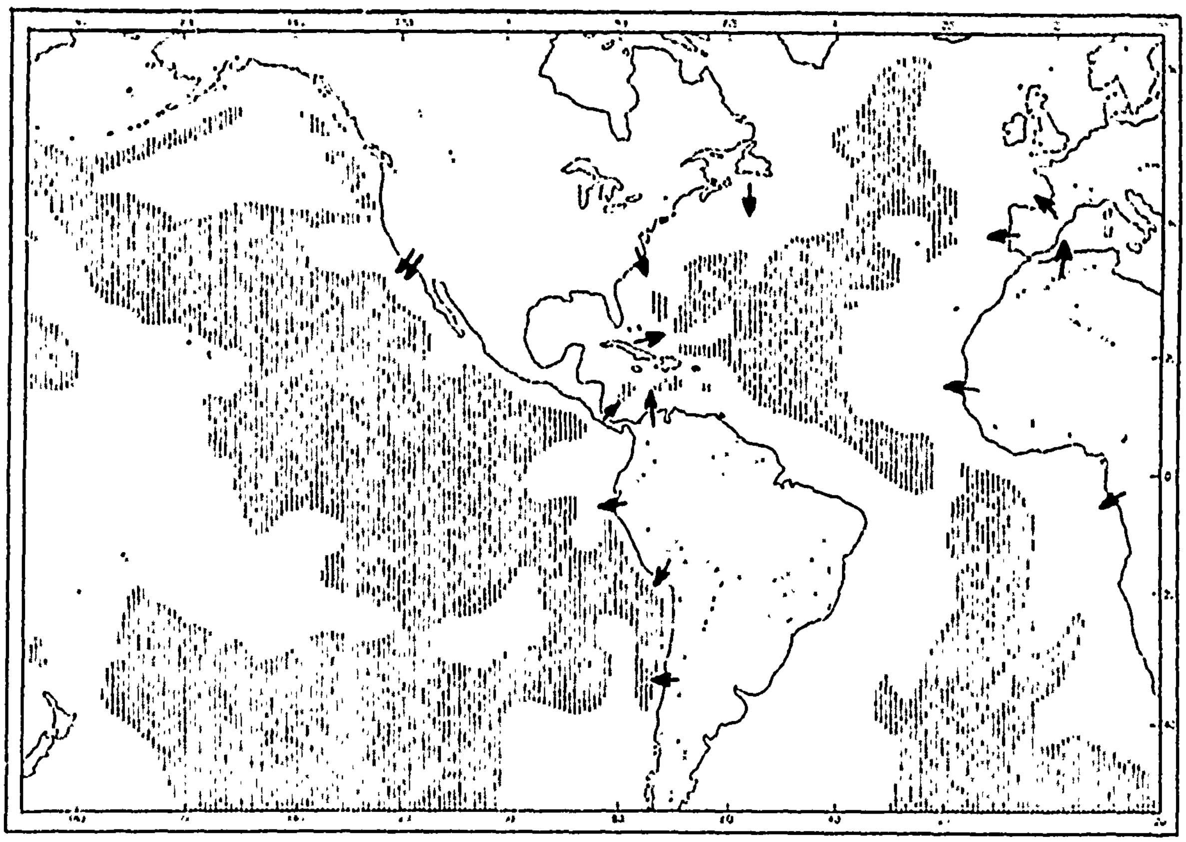


FIGURE 5.6

Where r_1 θ and z are the cylindrical coordinates

α is the coefficient of thermal expansion

T_o is the initial temperature before quench at time t=0

E is the modulus of elasticity

ν is the Poisson's ratio

b is the cylinder radius

β_n is defined from the roots of the Bessel Equation

$$J_o(\beta_n) = 0 \qquad P_n = \frac{k}{c\, p} \frac{\beta_n^2}{b^2}$$

k is the thermal conductivity

c is the heat capacity

p is the density of the cylinder

In order to determine whether the heat block-shield will crack, the maximum stresses are determined. These occur at t=o and r=b. Substituting into equations 5.7-5.9:

$$\sigma_r = 0 \tag{5.10}$$

$$\sigma_\theta = \sigma_z = \frac{2\alpha E\, T_o}{1-\nu} \sum_{n=1}^{\infty} \frac{2}{\beta_n^2} \tag{5.11}$$

It is found that the summation in equation 5.7 is

$$\sum_{n=1}^{\infty} \frac{1}{\beta_n^2} = \frac{1}{4} \quad \text{and} \tag{5.12}$$

$$\sigma_z = \frac{\alpha E\, T_o}{1-\nu} \tag{5.13}$$

For steel:

$$E = 27\text{-}29 \times 10^6 \text{ lb/in}^2$$

$$\alpha = 10\text{-}15 \times 10^{-6}/^\circ C$$

$$T_o = 594^\circ C$$

$$\nu = 0.27$$

from which it is found that $\sigma_z = 4.1 - 2.5 \times 10^5 \text{ lb/in}^2$. This is well in excess of the tensile strength of 60,000 psi. Fracture of the heat block-shield under these conditions is anticipated.

In conclusion, rapid, gross failure of the pressure vessel may result in heat block shield thermal fracture. Such fracture would probably expose one or more fuel capsules to the ocean environment. Thermal shock to the capsules is not considered a hazard since the capsule design has already been qualified for 1350°F to 32°F quench. The only foreseeable condition which could seriously threaten capsule integrity requires that the heat block-shield crack from thermal shock, but the capsules remain near or above operating temperature. In this case, the exposed capsules would probably break in about one year due to high temperature corrosion. No assessment has been made as to whether or not this type of failure is credible.

5.3 Fuel Transport and Population Interaction

The previous safety analyses have failed to reveal a credible mechanism that could completely fail the heat block-shield, and the fuel encapsulation exposing the fuel to seawater. The radioactivity content of the RTG is 5.1 MCi (assuming 148.9 Ci/W for ^{90}Sr from Ref. 40. This is contained in 7 capsules of 0.73 MCi each. Conservatively assuming diffusion independence and a linear dissolution rate of 1.0 mg/cm^2-day (Ref. 22) and a density of 5.03 g/cm^3 for average Sr_2TiO_4, the dimensional change is 2×10^{-4} inches/day or 142 years for total solution.

Strontium in seawater will impact man through the food chain. There is no fishing at the reference implacement depth (20,000 feet) so the connection between release at that depth and the food chain is quite tenuous. The SNAP 23A criterion for the maximum permissible "Strontium" concentration (MPCC) is 3.5×10^{-5} µCi/cc (Ref. 22).

Okubo (Ref. 22) presents a Gaussian diffusion model for seawater as:

$$S_c(r,\ t) = \frac{q/D}{2\sqrt{\pi}\ \omega r}\ \frac{2}{\sqrt{\pi}} \int_{y=\frac{r}{\omega t}}^{y=\infty} e^{-y^2}\, dy \quad 0<t<\tau_o \tag{5.14}$$

$$S_c(r,\ t) = \frac{q/D}{2\sqrt{\pi}\ \omega r}\ \frac{2}{\sqrt{\pi}} \int_{y=\frac{r}{\omega t}}^{y=\frac{r}{\omega(t-\tau_o)}} e^{-y^2}\, dy > t\ \tau_o \tag{5.15}$$

Where S_c is the source concentration at distance, R, from source at time, T, μ/cm^3

q is the continuous release rate, 1.83×10^{-2} Ci/sec

D is the diffusion layer thickness, 100 cm

ω is the diffusion velocity, 2.4 cm/sec (Ref. 22)

t is the time, sec

r is the radial distance from source, cm

τ_o is the total time required for complete dissolution

τ is the time span during fuel release, seconds

The dissolution time τ was found to be 142 years for these large capsules hence only Equation 5.14 need be evaluated.

Equation 5.14 is greatly simplified by noting that for $y \leq 0.1$, the integral is practically unity ($\geq .98$). To determine the radial distance at which S_c=MPCC is exceeded for distances closer than 6.18 km. As the fuel decays, this distance decreases. Figure 5.7 presents a plot of the radius at which MPCC is exceeded as a function of time.

In conclusion, if a hypothetical accident occurred such that all barriers protecting the ocean environment from the Sr_2TiO_4 fuel were removed, the MPCC derived for the sea food chain would be exceeded for distances less than 6.18 km to the RTG. This calculation is extremely conservative. First, it assumes that the RTG is sited in an environment normally related to the food chain. Such is not the case for the reference depth. Second, the calculation does not consider the presence of debris from the encapsulation, heat block-shield, sedimentation etc. All these will tend to reduce the solution rate.

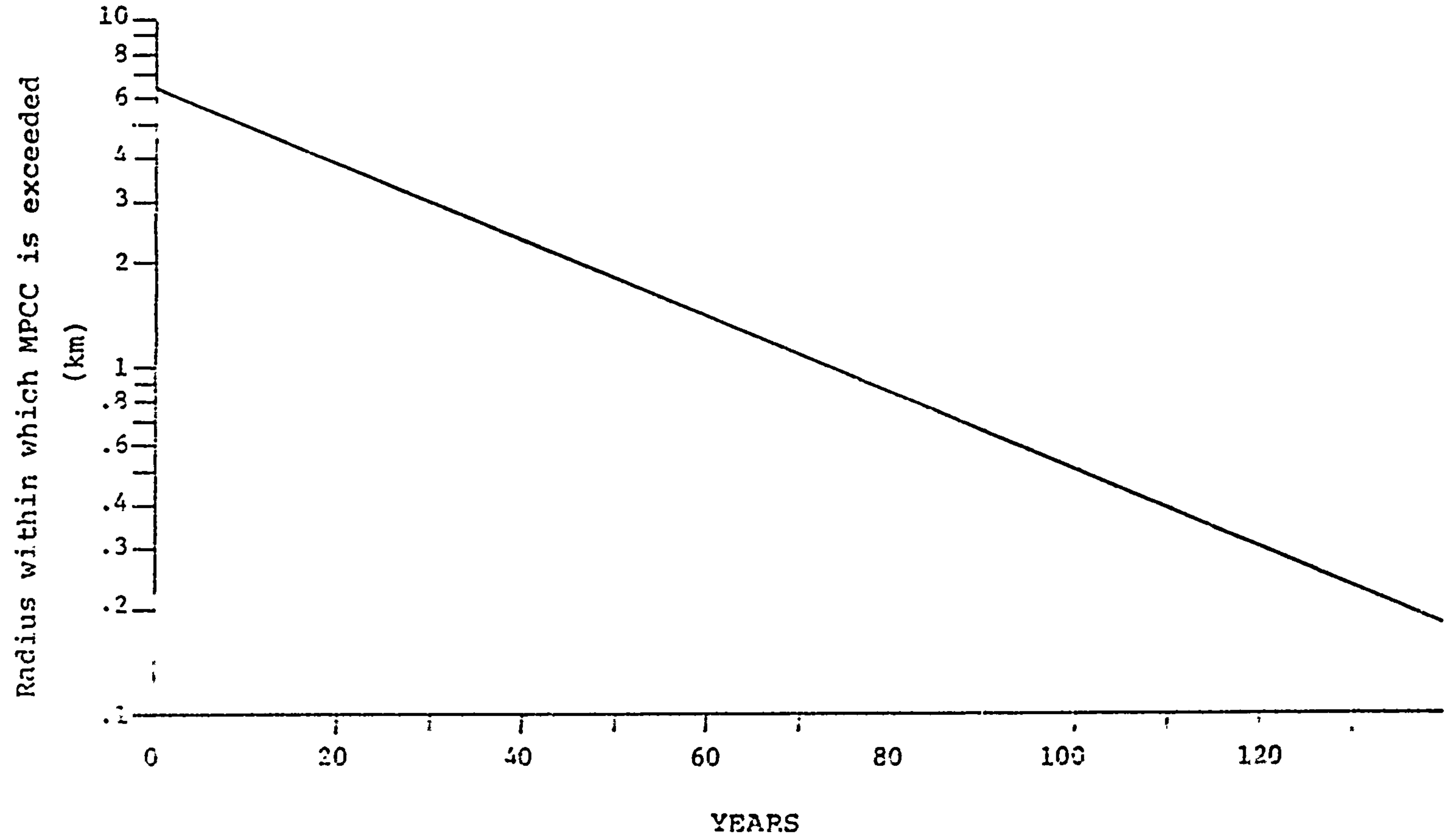


Figure 5.7 Radius within which MPCC is exceeded as a function of Time after RTG Construction.

REFERENCES

1. E. D. Arnold, Handbook of Shielding Requirements and Radiation Characteristics of Isotopic Power Sources for Terrestrial, Marine, and Space Applications, ORNL-3576 (April, 1964).

2. E. P. Blizard, "Analytical Methods of Shield Design," Chapter 11 in Shielding, Vol. III, Part B, of "Reactor Handbook," 2nd Edition, Rev., E. P. Blizard and L.S. Abbott, eds., Interscience, N.Y., 1962.

3. Anon., "Modification of Modified Point-Kernel Code Quad P5A," Science Applications, Inc., Huntsville, Ala., 1974.

4. M. Solomites and J. Stockton, "Modification of the Point Kernel Code-Quad P5A," Oak Ridge National Laboratory report ORNL-4181 July, 1968.

5. Lee Simmons, SAI Huntsville, private communication to Ralph Fullwood SAI Palo Alto, Jan. 13, 1975.

6. Private communication from Robert Carlton NAVFAC to Ralph Fullwood, SAI. December, 1974.

7. P. J. Roark, "Formulas for Stress and Strain, Fourth Edition, McGraw-Hill Book Co., New York, 1965, p. 354.

8. J. H. Keenan and F. C. Keyes, "Thermodynamic Properties of Steam," John Wiley and Sons, N.Y., 1936.

9. D. Mallinson Varian Associates, Palo Alto, California, private communication to R. Fullwood. December, 1974 referring to Varian model 925-40.

10. M. E. Lackey, "A Test of Fusible Insulation for a Proposed Isotopy Power Unit", Oak Ridge National Laboratory Report ORNL-TM-4422.

11. G. Yadigaroglu, A.G. Reinking and V.E.Schrock, "Spent Fuel Transportation Risks," Nuclear News, November, 1972.

12. Federal Highway Administration, 1969, "Accidents of Large Motor Carriers of Property," Department of Transportation, December, 1970.

13. Leimkuhler, "Trucking of Radioactive Materials: Trucking vs. Economy in Highway Transport," NYO-9773, 1963.

14. U. S. Atomic Energy Commission, "An Assessment of Accidental Risks in U. S. Commercial Nuclear Power Plants," WASH-1400, August, 1974.

15. Gibson, R., "The Safe Transport of Radioactive Material," Pergamon Press, 1966.

16. M. E. Lackey, "Thermal Test of the Heat Block-Shield for the Isotope Kilowatt Program," ORNL-TM-3806, March, 1973.

17. U. S. Atomic Energy Commission, "Environmental Survey of Transportation of Radioactive Material to and from Nuclear Power Plants," WASH-1238, December, 1972.

18. "Technical Investigation Supporting a 2-KW (e) RTG Final Design," NCEL, August, 1973.

19. Federal Register, Vol. 33, No. 230, November 1968, "Title 10 Part 71 - Packaging of Radioactive Material for Transport."

20. W. A. Brobst, "Transportation Accidents: How Probable?," Nuclear News, May, 1973.

21 Federal Register, Vol. 33, No. 194, October 1968, "Department of Transportation, Hazardous Materials Regulations Board."

22. Regulations for Safe Transport of Radioactive Materials, IAEA Safety Series, No. 6, 1967.

23. Westinghouse Astronuclear Laboratory: "Preliminary Safety Analysis Report," WANL-3800-42, February, 1970.

24. U.S. Atomic Energy Commission, "Design Response Spectra for Seismic Design of Nuclear Power Plants," Regulatory Guide 1.60, December, 1973.

25. Newmark, N.M., John A. Blume, and Kanwar K. Kapur, "Design Response Spectra for Nuclear Power Plants," ASCE Structural Engineering Meeting, San Francisco, April, 1973.

26. N. M. Newmark Consulting Engineering Services, "A Study of Vertical and Horizontal Earthquake Spectra," Urbana, Illinois, U. S. Atomic Energy Commission Contract No. AT(49-5)-2667, WASH 1255, April, 1973.

27. John A. Blume & Associates, "Recommendations for Shape of Earthquake Response Spectra," San Francisco, California, U. S. Atomic Energy Contract No. AT(49-5)-3011, WASH-1254, February, 1973.

28. K. R. Demars and D. G. Anderson,"Environmental Factors Affecting the Emplacement of Seafloor Installations," Naval Civil Engineering Laboratory R-744, 1973.

29. B. Gutenberg and C. F. Richter, "Seismicity of the Earth and Associated Phenomena," 2nd ed., N.J.Princeton University Press, 1954.

30. B. C. Heezen and M. Ewing, "Turbidity Currents and Submarine Slumps and the 1929 Grand Banks Earthquake," American Journal of Science 250, 849-873 (1952).

31. B. C. Heezen, M. Tharp, M. Ewing, "The Floors of the Ocean, 1 North Atlantic," Geological Society of America Spec. Paper, 65, 122 (1959).

32. B. C. Heezen, "The Origin of Submarine Canyons," Scientific American W. H. Freeman and Co., San Francisco (1971).

33. J. Milne, "Sub-oceanic Changes, 3 Cable Fracture," Geog. Journal 10, 259-284 (1897).

34. K. Hunkins and H. Kutschale, "Quaternary Sediment in the Arctic Ocean," Progress in Oceanography Vol. 4 Pergammon Press, New York (1964).

35. F. P. Shepard, "Importance of Submarine Valleys in Funneling Sediments to the Deep Sea," Progress in Oceanography, Vol. 3, Pergammon Press, New York (1963).

36. F. P. Shepard, "Submarine Geology (2nd Edition) Harper and Rowe, New York (1963).

37. H. R. Gould, "Some Quantitative Aspects of Lake Mead Turbidity Currents," presented at the symposium Turbidity Currents Soc. Econ. Paleont. and Mineralog., Spec. Pub. (2), 34-52.

38. U.S.AEC, "Analysis of Pressure Vessel Statistics from Fossil-Fueled Power Plant Service and Assessment of Reactor Vessel Reliability in Nuclear Power Plant Service," WASH-1318, May, 1974.

<u>References</u> (continued)

39. S. Timoshenko and J. N. Goodier, "Theory of Elasticity," Second Edition, McGraw-Hill Book Co., New York, 1951.

40. R. A. Robinson, "Isotope Kilowatt Program, Task I - Conceptual Design and Evaluation," ORNL-TM-2366, January, 1970.

41. M. G. Fontana and N. D. Greene, "Corrosion Engineering," McGraw-Hill Book Co., page 96, 1967.

42. Mayes, T. C., McGrew, J., "ANPP Corrosion Program Final Summary Report," USAEC Report MND-E-2727, Feb., 1962.

43. Cheng, C. F. and Tymchyn, H.L., "Stress Corrosion of Inconel in 550°F. "Aerated Sea Water," USAEC Report KAPL-M-CC-3 Feb., 1961.

44. Cheng, C. F., Tymchyn, H.L., "Chloride Stress Corrosion Cracking of Ni-Cr-Fe Alloys," USAEC Report KAPL-M-CC-3, April 3, 1963.

45. Copson, H. R., Economy, G., "Effect of some Environmental Conditions on Stress-Corrosion Behavior of Nickel Chromium-Iron Alloys in Pressurized Water," Paper presented at the International Nickel Power Conf., Lausanne, Switzerland, 1967; also Corrosion, <u>24</u>, (3), 55-65, March, 1968.

46. U. S. Atomic Energy Commission, "The Safety of Nuclear Power Reactors," WASH-1250, July, 1973.

47. Groewall, B., et al., "Intercrystalline Stress-Corrosion Cracking of Inconel-600 Inspection Tubes in the Agesta Reactor," AE-245, August, 1966.

48. "Fuel Cask Wins AEC Nod," <u>Nuclear News</u>, pg. 54, March, 1973.

49. B. J. Garrick, O. C. Baldonado and W. C. Geckler, "Estimating the Risk Involved in Transport of Hazardous Materials," presented at CREST meeting, Munich, Germany, May, 1971.

50. Handbook of Chemistry and Physics, 42nd Edition, 1960.

6.0 Required Research, Development and Testing

During the analyses, reviews, and discussions conducted to complete this PSAR, several areas have been determined to be inadequately defined and requiring further research, development, or testing to provide final answers. These areas are presented below under the headings "RTG Design" and "RTG Operations".

6.1 RTG Design

6.1.1 Fuel

The fuel is adequately defined and suitable for use in the 2KW RTG system.

6.1.2. Fuel Compatibility

Data that demonstrates that Sr_2TiO_4 is compatible for a ten year lifetime with either containment material (Hastelloy C-276 or Inconel-625) has not been developed. It is recommended that a test program be instituted to demonstrate the extent of compatibility of Sr_2TiO_4 with the containment materials under consideration.

6.1.3. Capsules

6.1.3.1 Materials

Both alloys considered (Hastelloy C-276 and Inconel-625 appeared adequate for normal operational conditions within the RTG. However, neither alloy appears capable of resisting a high temperature salt water corrosion environment for more than one year. These judgments are based on tests discussed in the references which are not exact duplicates of the expected environments. It is recommended that both materials undergo qualification test programs to establish their relative abilities to survive the various credible accident situations proposed in this PSAR.

It is also recommended that two alloys featuring higher chromium content, Haynes-188 and Inconel-617 be examined (see Appendix C). These alloys offer better corrosion resistance and appear better suited to the operating temperatures that the fuel capsules will experience.

6.1.3.2 Welding Procedure

The plasma arc weld used to seal the capsules proved inadequate during the impact test conducted for this program. An electron beam weld has been recommended in Ref. 1. It is recommended that this welding technique be subject to impact testing before a design change is specified.

6.1.3.3 Age Hardening

The capsule impact tests of Reference 2 were apparently conducted with an unaged capsule. Data from the references (Appendix C) indicate that both alloys suffer from high temperature age hardening. It is recommended that a new impact test program be conducted utilizing aged capsules.

6.1.4 Heat Accumulator Block

6.1.4.1 Materials

A simplified analysis (Appendix B) indicates that the SAE1010 Heat Accumulator Block may crack during a fast seawater quench. If this occurs, the capsules may be subject to rapid corrosion by hot seawater. The complex shape of the heat accumulator block as well as the variety of possible quenching modes should be investigated thoroughly. It is recommended that an analysis and test program be conducted to determine whether or not the Heat Accumulator Block will crack under a worst-case quenching situation.

6.1.4.2 Support Skirt

The Heat Accumulator Block is separated from the pressure vessel by thermal insulation. This insulation is not capable of rigidly supporting the block during static or dynamic loads. Any relative movement between the block and the pressure vessel will impose severe loads on the heat pipes, which are mounted to both. It is recommended that a support structure be designed to prevent any horizontal, vertical or rotational movement of the block with respect to the pressure vessel.

6.1.4.3 Radiation Shielding

The radiation shielding analysis presented in Section 5.1.1 indicates that the present Heat Accumulator Block design is slightly inadequate (i.e., greater than the 200 mr/hour maximum). The point kernel method utilized is known to be somewhat conservative. However, to insure compliance with the applicable regulations, it is recommended that a more accurate Monte Carlo analysis be completed on the BOL Heat Accumulator Block.

6.1.5 Heat Pipes

6.1.5.1 Working Fluid-Compatibility

The present potassium heat pipes appear to be somewhat over-designed in terms of high temperature heat transfer capability. It is recommended that:

1. Cesium heat pipes be investigated. These would have a higher vapor pressure at lower temperatures and would reduce any installation start-up problems which may occur.

2. In view of the fact that a test program to develop compatibility data between the potassium working fluid and the stainless steel wick and pipe wall materials is required, it is recommended that Nickel-Potassium heat pipes be investigated, as some compatibility data has been collected for Nickel-Potassium pipes after approximately 5 years of operation at 600°C. Should Nickel be selected as the heat block material (see section 7.1.3.1) greater material compatibility between the heat pipes and heat block will result.

6.1.5.2 Attitude Capability

Most heat pipes suffer reduced heat transfer capability as the condenser end is lowered with respect to the evaporator end. When the condenser is lower than the evaporator, heat pipe action essentially ceases. The present heat pipe design is adequate for operation to at least 60° off vertical. If the RTG tips over during installation, the heat pipes will be tilted more than 60° and a system shutdown will occur, even if the tipping is only temporary. It is recommended that heat pipes capable of operating at greater than 60° (increasing up to 90°+) be investigated.

6.1.5.3 Lifetime

The present heat pipe design is optimized for a five-year mission. The updated mission lifetime of ten years requires that the heat pipes be designed, optimized, and tested to simulate a ten-year mission.

6.1.6 Thermoelectric Modules - Lifetime

The present thermoelectric modules are designed and optimized for a five-year mission. It is recommended that a design and test program be conducted to satisfy the new 10 year mission requirement.

6.1.7 Insulation

6.1.7.1 Melt Temperature

The melt temperature of the fusible aluminum insulation is only slightly higher than its expected operating temperature.

It is recommended that a thermal analysis of the insulation be conducted to determine the possibility of premature meltdown during the assembly, handling, transportation, installation or recovery phases of the mission.

6.1.8 Pressure Vessel

6.1.8.1 Manufacturing Method

The pressure vessel may be manufactured by one or more of the following methods; casting, forging, or rolling. No clear technical advantages were found for any method. It is recommended that the best (probably, the most cost-effective) method be determined.

6.1.8.2 Closure Method

The bolted closure has been recommended over the welded closure in this report (See Appendix C). It is recommended that the final bolted closure design be proof-tested with prototype hardware.

6.1.8.3 Hybrid Closure

It has been found during this study that a combination joint utilizing bolted flanges for rigidity and a thin peripheral weld for leak tightness appears to offer advantages over either a bolted closure or a welded closure alone. It is recommended that this type of joint be investigated for feasibility and reliability.

6.1.8.4. Pressure Relief

If the pressure vessel were to develop a slow leak during the mission, the internal pressure will tend to rise to the ambient pressure. During recovery, as the RTG is raised to the surface, the outflow through this small leak may not be sufficient to equilibrate the pressure. The internal pressure will become much greater than the decreasing exterior pressure. Hoisting such a highly pressurized device aboard ship and attempting disassembly may be hazardous. It is recommended that some form of internal pressure relief be designed and tested for the pressure vessel so that the RTG can be transported, handled, and disassembled safely.

6.1.9 Foundation

6.1.9.1 Dimensions

Reference 3 indicates that the present RTG foundation dimensions (14 feet square) are limited by emplacement ship clearances. These maximum dimensions result in an ocean bottom

loading approaching one pound per square inch (excluding floatation devices). This may limit the number of acceptable mission sites. A trade-off study of foundation dimensions, floatation requirements and site suitability is recommended.

6.1.9.2 Release Mechanism

The joint between the RTG and its foundation must prevent the RTG from tipping during emplacement and operation. During recovery, the foundation is not needed and would be a substantial extra weight to lift. For this reason, the present design calls for corroding magnesium bolts between the RTG and its foundation. These bolts will corrode soon after emplacement and later allow the RTG to be lifted free during the recovery phase. It is recommended that this method be investigated further and tested for adequacy.

6.2 RTG Operational Procedures

The various procedures during the life cycle of the RTG system must be adequately defined before a final safety analysis report can be completed. At the present time, none of the operational procedures, (assembly, handling, transportation emplacement, or recovery) have been adequately defined in the literature. It is recommended that these procedures be defined.

REFERENCES

1. Bradley, "Isotope Kilowatt Program Fuel Capsule Testing," ORNL-TM-4350, October, 1973.

2. C. L. Ottinger, et al, "Evaluation of Production of 34 KW (th) Strontium-90 Fueled Heat Source Assemblies at Oak Ridge National Laboratory," ORNL Report, May, 1974.

3. J. F. McCartney, et al, "Technical Investigation Supporting a 2 KW (e) RTG Final Design," NCEL Technical Note N-1304, August, 1973.

7.0 Recommended Design and/or Procedural Modifications

The following minimum modifications are hereby recommended for the 2 KW(e) RTG program:

7.1 RTG Design

7.1.1 Fuel - None

7.1.2 Capsules

7.1.2.1 Material

Hastelloy C-276 and Inconel-625 superalloys appear approximately equal in ability to withstand the operational and credible accident environment. Data that demonstrates the Sr_2TiO_4 fuel is compatible for a ten year lifetime with either containment material has not been developed. A clear choice can be made only after the research and development program recommended in Section 6 of this report is completed. Availability at the time of procurement will probably be a factor in the material selection.

7.1.2.2 End Weld

The plasma arc capsule closure weld does not appear able to resist the nominal impact test. An electron beam weld, which provides for better penetration and control is recommended.

7.1.3 Heat Accumulator Block

7.1.3.1 Material

The present RTG design specifies an SAE1010 steel heat accumulator block. The iron constituting the steel undergoes two solid phase transitions. The one at 1652°F causes a 1.6% volume decrease. This can cause severe anisotropic thermal stresses following a heat pipe shutdown. Additionally, the steel block is electrochemically more active than the fuel capsules, promoting capsule corrosion. For these and other reasons, it is recommended that Nickel-201 alloy be substituted for SAE1010 steel as the heat accumulator block material.

7.1.3.2 Heat Accumulator Block - Lateral Support

In order to prevent lateral movement between the heat accumulator block and the pressure vessel, which could damage the heat pipes, it is recommended that a rigid support skirt be included in the system design.

7.1.4 Heat Pipes

It is recommended that the heat pipes be redesigned for horizontal (90°) operational capability to prevent any system damage should the RTG be temporarily tilted during any phase of the mission.

7.1.5 Thermoelectric Module

The present design for the TEM's is not adequate to meet the ten year lifetime design criterion. The modules must be redesigned accordingly.

7.1.6 Pressure Vessel

7.1.6.1 Closure Joint

The use of a bolted closure joint is recommended over a welded joint. Either joint can satisfy the mission objectives, but the welded joint greatly decreases accessibility to the internal parts should tests or component replacement become necessary after assembly and before implacement.

A hybrid joint utilizing aspects of both the bolted and welded closures has also been recommended for consideration. (See Section 6 and Appendix A.)

7.1.6.2 Pressure Relief Device

It is mandatory that a method of relieving high internal pressures be incorporated into the pressure vessel. Such pressures may occur during the retrieval operation if a very small leak has allowed a substantial increase in internal pressure. If the leak is small enough it may not vent the internal pressure quickly enough during the lifting operation.

7.1.7 Pressure Vessel - None

7.2 RTG Operation

7.2.1 Data Acquisition

It is recommended that the RTG condition be monitored during emplacement to ensure that no mechanical or electrical failures occur. This would allow immediate recovery of the RTG while it is still connected with the emplacement vessel.

In addition, it would be desirable to include a separate data acquisition and backup transmission system to provide information on the functioning of the power supply during its entire lifetime. RTG parameters that could be monitored are: output voltage, current, component temperatures, RTG attitude, and the presence of moisture inside the pressure hull.

8.0 Summary

8.1 Program Status

The 2 KW(e) RTG program has advanced toward completion, as indicated in Table 8-1.

8.2 Assumptions

The 2 KW(e) RTG program, as defined by the reference material, is not sufficiently described in all areas to allow a comprehensive safety analysis. Where necessary, RTG components and/or activities have been postulated based on experience from earlier RTG programs. These assumptions have been simplified as much as possible in order not to limit the value or applicability of the PSAR. All such assumptions are stated explicitly throughout the body of the PSAR.

8.3 RTG Components

8.3.1 Capsules

The capsule design utilizing EB welds on both ends appears adequate whether Hastelloy C-276 or Inconel-625 is used with the following exception: A fast seawater quenching of the Heat Block-Shield may cause cracking and allow capsule exposure to seawater. Capsule exposure to high temperature (>1,000°F) seawater will cause accelerated corrosion rates and allow fuel release in one to two years (see Appendix C). Whether or not the RTG can maintain such a high temperature under any condition following a rapid seawater leak has not been determined.

Alternate alloys, Haynes-188 and Inconel-617 should be examined for use as fuel capsule materials. Both offer better corrosion resistance due to higher chromium content, and appear suited to use in a high temperature (>1,000°F) environment.

8.3.2 Heat Block-Shield - Shielding Capabilities

The Heat Block-Shield appears marginally inadequate with respect to surface radiation flux allowed by 49CFR-173 during transportation and handling. A more accurate analysis than that conducted herein is required to ensure that the Heat Block-Shield complies with all applicable federal regulations.

TABLE 8-1 PROGRAM STATUS

RTG Component	Development Status (From References Reviewed)	Remaining Development
Fuel	Fully Developed	None
Fuel Liner	Conceptual Design	Fuel Compatibility Tests
Fuel Capsule	Preliminary Design, Prototype Model, Impact Test	End Closure, Joint Design, Final Materials Choice
Heat Pipes	Preliminary Design, Prototype Model, Functional Tests	Redesign to 90° (Horizontal) Capability and Ten Year Life
Heat Block-Shield	Preliminary Design, Prototype Model, Functional Tests	Thermal Shock Tests, Final Materials Choice
Fusible Insulation	Preliminary Design, Prototype Model, Functional and Melt Tests	Assure that Operating Temperature is Below Melting Temperature Range
Thermoelectric Modules	Preliminary Design, Prototype Models, Performance Tests	Re-optimize for Ten Year Mission Life
Pressure Vessel	Preliminary Design	Pressure Relief Valve, Final Joint Design
Foundation	Conceptual Design	Final Design Including Materials Choice, Integration with handling Procedures, and Dimensions Compatible with Transport Vessel and Site Bearing Strength
RTG Instrumentation	Undefined	Define RTG Instrumentation

TABLE 8-1 (cont'd.)

RTG Activity	Status (See Section 3)
Assembly	Undefined
Handling	Undefined
Transportation	Partially Defined
Emplacement	Partially Defined
Operation	Defined
Recovery	Partially Defined
Disassembly	Undefined
RTG System	
System Analysis	Complete Analysis Required
System Testing	Performance Tests Required

8.3.3 Heat Block-Shield - Thermal Shock Resistance

It appears possible to crack the Heat Block-Shield by quenching in seawater (caused by a pressure vessel failure). The possible magnitude of such cracking has not been determined. Full scale thermal shock tests are recommended.

8.3.4 Heat Block-Shield - Material

It is recommended that Nickel-201 alloy be used in lieu of SAE1010 steel for manufacturing the Heat Block-Shield.

8.3.5 Heat Pipes - Design

The current heat pipe design provides adequate heat transport to the TEM's in attitudes from the vertical (condenser above evaporator) to 60° below vertical. However, operation to at least 90° (horizontal) is recommended.

8.3.6 Heat Pipes - Working Fluid - Compatibility

Since adequate compatibility between the fluid and pipe walls for a ten year life has yet to be demonstrated for the present design, it is recommended that Potassium-Nickel heat pipes be investigated for use in the 2 KW(e) RTG. Some five year compatibility information for such heat pipes has been collected. Should the Nickel heat block-shield recommended in 7.1.3.1 be adopted, Nickel heat pipes would provide the additional benefit of assuring material compatibility between the heat pipes and heat block-shield.

It is also recommended that for the existing heat pipe design, cesium be investigated as a replacement for the potassium working fluid now specified.

8.3.7 Fusible Insulation - Operating Temperature

The melt temperature of the present fusible insulation is close to its expected normal operating temperature. It is recommended that either the RTG operating temperature be lowered or the insulation melt temperature be raised to allow for a greater margin of safety.

8.3.8 Thermoelectric Modules (TEM's) - Lifetime

The present TEM design is based on a five (5) year lifetime and appears adequate. The system must be re-optimized for a ten (10) year mission.

8.3.9 Pressure Vessel - Seal

A bolted joint is recommended over a welded joint. A hybrid joing, utilizing bolts to provide structural rigidity and a seal weld to provide leak tightness offers advantages and is recommended for further study.

8.3.10 Pressure Vessel - Pressure Relief

A pressure relief device is recommended for the pressure vessel to vent seawater pressure which has slowly accumulated in the RTG during its mission operation.

8.4 Conclusion

Under the reference design given for the assembled RTG, no safety problems were identified. It is emphasized, however, that many information voids in the reference design exist. The research, development, and testing programs that are required to fill these voids have been identified and are listed in Section 6. The design of many of the RTG components, including materials selections, will be affected by the results of these programs.

A potential problem during the assembly phase, that of radiation streaming from the empty heat pipe holes of the heat block-shield was identified (see section 5.1.1). A more detailed analysis must be conducted before it can be conclusively determined that the amount of radiation does, in fact, exceed federal regulation.

Additional information on the procedural aspects (Assembly, Handling, Transportation, etc.) of the RTG is required. It is also noted that the emplacement site considered was a hypothetical case. It is possible that specific sites may present hazards not considered in this analysis. Examples of such hazards, for a shallow site emplacement are; the activity of man, surface wave action or stronger water currents, and sedimentation rates. These and other factors could present performance and reliability problems. Also, a shallow site release of radioactive material would have a greater opportunity to be taken directly into the food chain than at the referenced depth of 20,000 ft.

It is apparent, then, that much information is required before either a complete system analysis can be conducted or all aspects of risk to public safety can be evaluated. The areas of missing information detailed above are not intended to be complete, but are indicative of the extent of work required before a more exhaustive analysis can be undertaken.

APPENDIX A

PRESSURE VESSEL CLOSURE OPTIONS

1.0 INTRODUCTION

A comparison of considerations integral to the performance of a welded joint as opposed to a bolted closure for the pressure hull of a 2KW(e) Radioisotope Thermoelectric Generator designed for deep sea (20,000 feet) use has been performed. An externally ring stiffened cylindrical hull structure, as shown in Figure A.1 (Ref. 1) is assumed. Since the greatest impact of the choice of closure is in its effect on the entire pressure hull, an examination of all pressure hull considerations is required. As a result, the scope of this section is not limited to the closure, but includes the effects of each closure choice on the pressure hull.

2.0 DESCRIPTION OF CLOSURE METHODS

This comparison assumes a configuration for the Weld joint as shown in Figure A.2. The bolted closure is shown in Figure A.3. The bolted closure includes a flat elastomer O-ring seal at the flange contact surfaces. This material assumption is consistent with the probable selection of BUNA-N for the O-ring. It is recognized that the O-ring configuration selected for the final design will represent the experience and preference of the designer. Double O-ring systems with a groove cut for the outside ring, or grooves for both rings are a possibility. The purpose of the designs of Figures A.2 and A.3 is to provide a base point for the comparison that is consistent with good engineering practices. It is recognized that they may be modified by the final designer.

3.0 CONSIDERATIONS

3.1 Codes, Specifications, and Standards

The following were used in conjunction with the preparation of this document:

MIL-S-16216H (SHIPS)
MIL-S-23008B (SHIPS)
MIL-E-23765/2A (SHIPS)
MIL-E-22749 (SHIPS) with Amendment 11
MIL-E-22200F
MIL-E-19822A (SHIPS) with Amendment 4
ASME Boiler and Pressure Vessel Code Section III, 1971;
  Section III Addenda, 1972; and Section VIII, 1971.

Additional references are listed in Section 6.

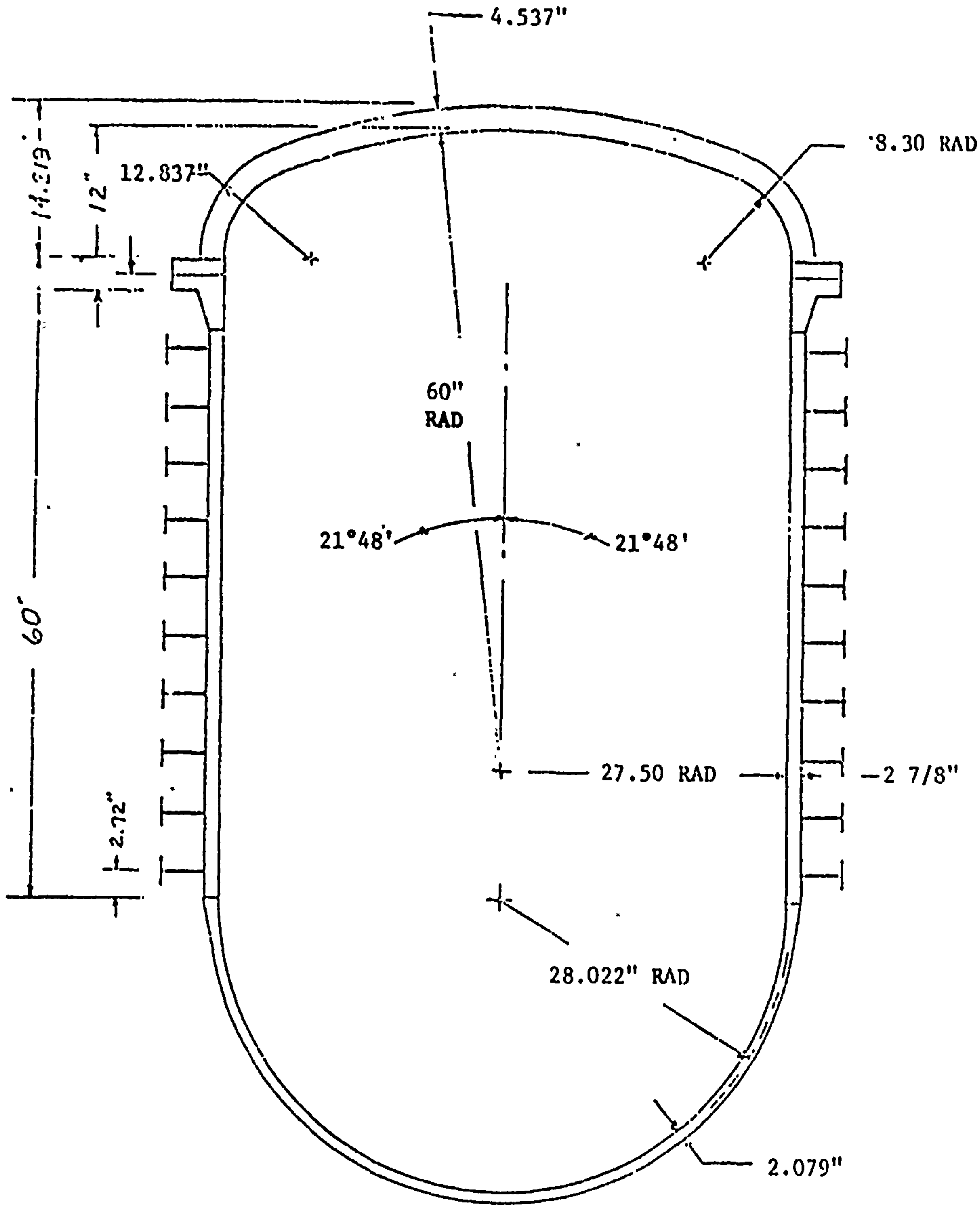


Figure A.1
HULL CONFIGURATION - HY-100 - STEEL (20,000' APPLICATION)

PROBABLE WELD CLOSURE CONFIGURATION

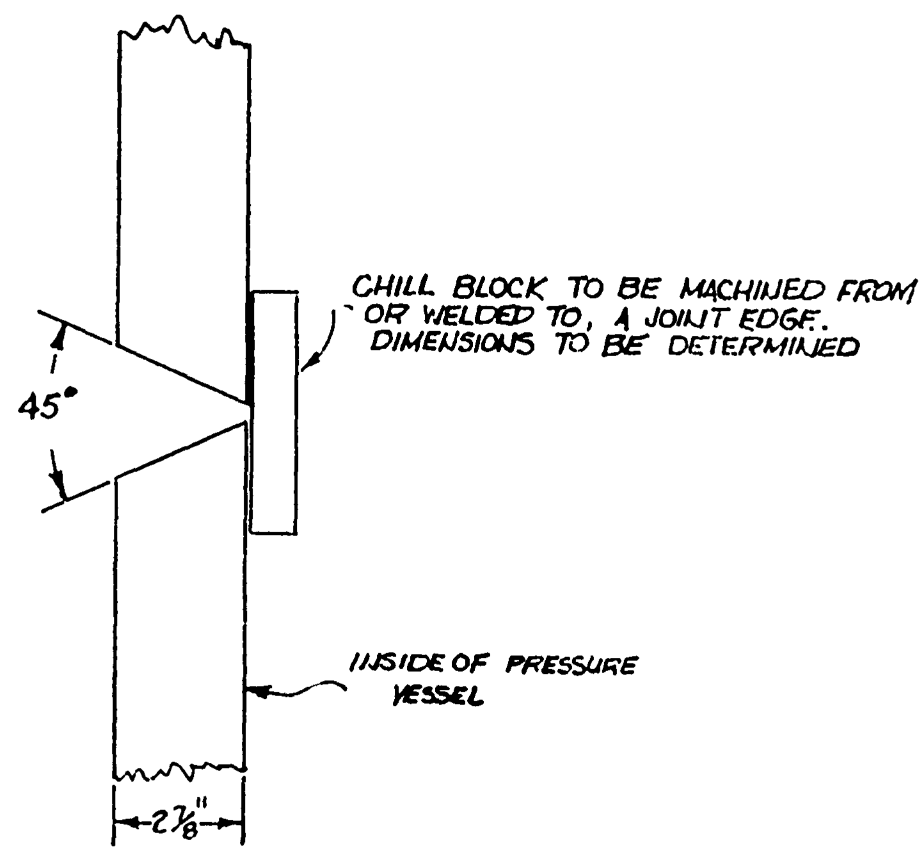
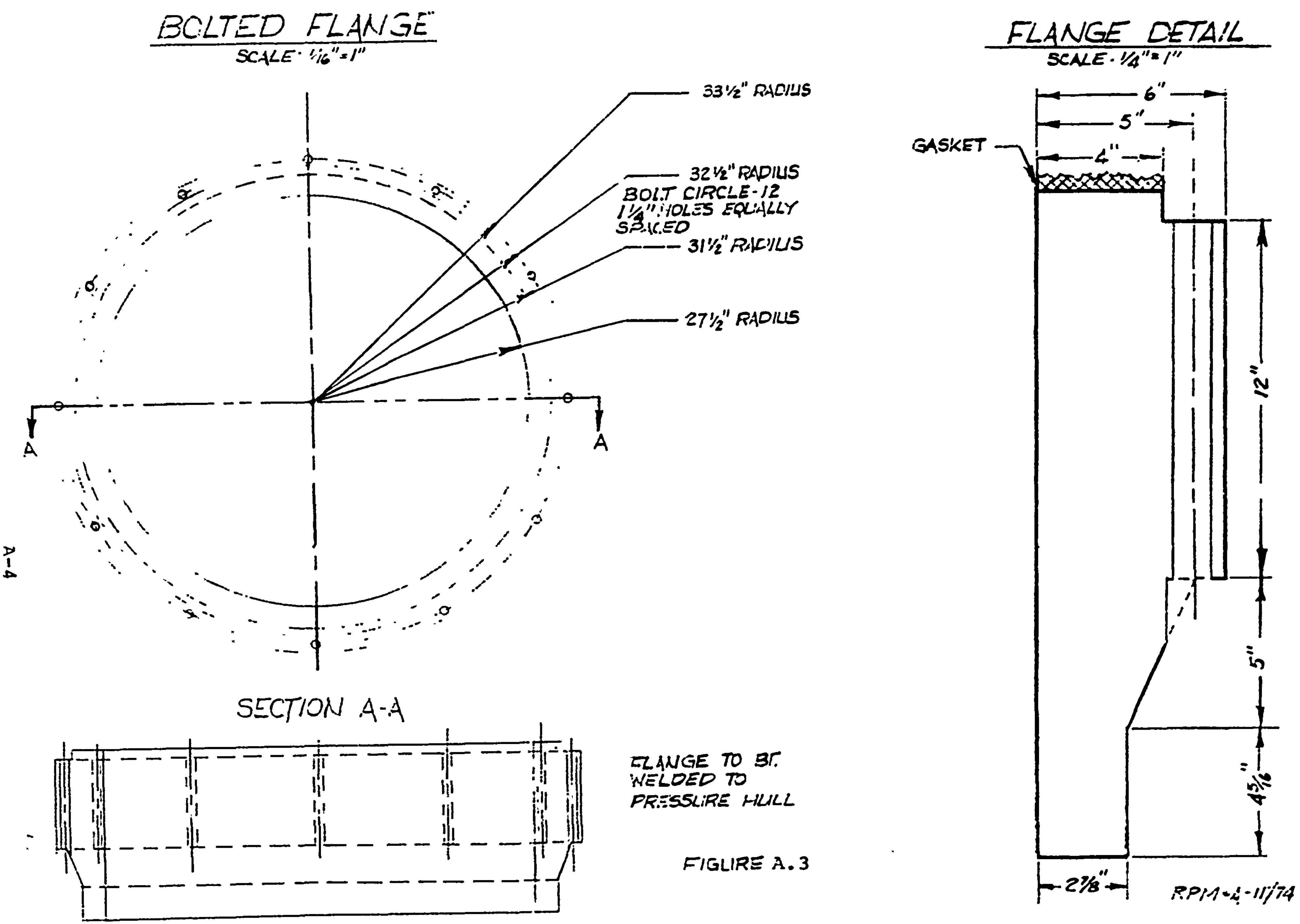


FIGURE A.2

RFM-A - 11/74



BOLTED FLANGE
SCALE · 1/16" = 1"
33 1/2" RADIUS
32 1/2" RADIUS
BOLT CIRCLE - 12
1 1/4" HOLES EQUALLY SPACED
31 1/2" RADIUS
27 1/2" RADIUS
A
A
SECTION A-A
FLANGE TO BE WELDED TO PRESSURE HULL
FLANGE DETAIL
SCALE · 1/4" = 1"
GASKET
6"
5"
4"
12"
5"
4 5/16"
2 7/8"
RPM-4-11/74

FIGURE A.3

3.2 Materials

The pressure hull material is HY-100 steel. This material is available in plate, bar, billet, and cast forms. It can be welded by metal arc, submerged arc, and shield arc processes, and is machinable. The hull design for the RTG recommended by NSRDC, if fabricated from plate stock will require dimensions of approximately 182" length, 60" width and 2.875" thickness. These dimensions are well within the capabilities of manufacturing mills (Ref. 4,5). Orders for this material require a lead time of 1/2 to 1 year (Ref. 4,5). Properties of HY-100 steel are listed in Tables A-1 to A-3 following:

TABLE A-1

HY-100 MECHANICAL PROPERTIES
(Ref. 6,7)

Type	Plate	Cast
Thickness (in.)	5/8 to 3 (incl.)	--
Yield Strength, (.2% offset - psi)	100,000-115,000	100,000-120,000
Tensile Strength	--	--
Elongation in 2 in. (min.%)	18	18
Reduction in Area (min.%)		
Longitudinal	50	--
Transverse	45	30
Charpy V-Notch Impact (ft./lbs.)		
(minimum, avg. of 3 specimens)		
Longitudinal (at Temperature °F)	50 (-120°F) to 2"	
	30 (-120°F) over 2"	

TABLE A-2

HY-100 CHEMICAL COMPOSITION (%-LADLE ANALYSIS)
(Ref. 6,7)

Type	Plate	Cast
C	.2 max	.22 max
Mn	.10/.40	.55/.75
P	.025 max (b)	.020 max
S	.025 max (b)	.015 max
Si	.15/.3	.5 max
Ni	2.25/3.5	2.75/3.5
Cr	1. /1.8	1.35/1.85
Mo	.2/.6	.3/.6
Ti (a)	.02	.02
V (a)	.03	.03
Cu (a)	.25	.20
Fe	Remainder	Remainder

(a) Maximum residuals permitted
(b) The combined phosphorus and sulphur content shall not exceed .045%.

TABLE A-3

TYPICAL ENGINEERING PROPERTIES (PLATE)
(Ref. 7)

Density (lb./in.^{3})	.283
Modulus of Elasticity (psi)	28×10^6 to 30×10^6
Coefficient of Linear Expansion (in/in/$^{\circ}$F, 80° -1200°F)	7.1×10^{-6}
Electrical Resistivity (microhm-cm at 70°F)	30.3

TABLE A-3 (continued)

TYPICAL ENGINEERING PROPERTIES (PLATE)
(Ref. 7)

Typical Notch Toughness Properties:	
Nil Ductility Temperature (°F)	-160
Fracture Transition, Elastic (°F)	-110
Fracture Transition, Plastic (°F)	-65
Charpy V-Notch Shear Energy Shelf Level (ft-lb)	110
Specific Heat (BTU/lb/°F at 70°F)	.110
Thermal Conductivity (BTU/sq.ft./hr./°F/in.)	227

3.3 Corrosion Properties

The corrosion properties of HY-100 steel submerged in ocean water are known to be similar to the other high strength low alloy (typically 3-4%) steels. Approximately linear losses of 3 to 4 mils per year (four year data) have been reported in stagnant seawater (Ref.8). In seawater flowing at 2 feet per second, losses of 8 to 9 mils were reported after one year, and 26 to 27 mils after four years of exposure (Ref.8). Three year corrosion data for a high strength low alloy (HSLA) steel of the same chemical composition as HY-100 were reported for 2 deep sea locations. Results are summarized in Table A 4 below. Data reported from the same experiment for Low Carbon (1010) steel are listed for comparative purposes (Ref. 9).

TABLE A-4

	Corrosion Rate (mpy)			
	Atlantic Ocean 5,600 ft.		Pacific Ocean 5,500 ft.	
Exposure Time	HSLA Steel	1010 Steel	HSLA Steel	1010 Steel
100 days	3.7	4.9	4.7	3.0
3 years	1.8	1.8	.5	1.0

As previously discussed, for purposes of determining a flanged joint design, an elastomer O-ring material such as BUNA-N is assumed. Electrode material for the welded closure will be determined by the weld process chosen. This will be discussed in Section 3.4.

3.4 Fabrication

This section considers possible fabrication methods for both the RTG pressure hull and its closure joint. Due to the size of the vessel, few fabricators exist with adequate equipment capabilities. The following fabrication information was gained primarily through discussions with key personnel in such organizations (Ref. 10, 11, and 12).

For the pressure vessel, one possible method is to roll form a plate into the cylindrical shape. A structural weld will bond the lateral seam formed in this process. Both end closures can be formed by forging, with a weldment required to attach the hemispherical end to the cylinder walls. Machining of the end closures will be required after forging to achieve specific geometric tolerance requirements.

If casting were chosen as the fabrication method, material properties and casting procedures will be dictated by Military Specification MIL-S-23008B (SHIPS). However, casting offers no advantages over forging with regard to obtaining the desired geometry, but does offer additional complexities in the fabrication process. Special attention to vacuum degassing procedures is required. It may even be necessary to pour the molten material in a vacuum to minimize scaling caused by hydrogen reactions (Ref.11).

A more likely possibility is to forge the entire vessel. Circumferential welds may be required about the cylinder side walls. (This will be determined by the design and capabilities of the fabricator.) Machining to tolerances will be required.

To manufacture the appropriate closure joint, either bolted or welded, or to machine the hull to desired geometry and tolerances, a turning operation will be required. This will most likely be milling, and, to avoid any detrimental effects caused by gravity, vertical milling is probable. It is established that machine processes can be performed to ± .005 inches (Ref.10). Out of roundness conditions of 1/16 inch have been seen for 8 foot diameters in the Alvin program with a maximum of 1/8 inch permitted (Ref. 13). As HY-100 was the material in this program, it is reasonable to expect the same parameters

for the RTG vessel. This is consistent with the NSRDC design (Ref. 1) for the RTG.

If the final closure is a bolted flange, the flange faces will probably be fabricated separate from the hull and welded to it. At this point the completed pressure hull should be pressure tested to determine the effectiveness of the bolted closure.

A welded final closure will require a chill block that is either machined or welded to the interior of one of the edges (see Figure A.1).

Pre-assembly welding techniques required during fabrication will now be discussed. As previously mentioned plain metal arc, gas shielded arc, or submerged arc welding may be used with HY-100 steel with yield stresses of approximately 100,000 psi obtainable. From fabrication experience it has been determined that speed and reliability advantages characterize the submerged arc process over the gas shielded arc process (Ref. 10.) Plain metal arc welding is the slowest of the three processes and is not recommended (Ref. 13). As a result, submerged and shielded arc processes will be reviewed in-depth. Military Specification MIL-E-23765/2A recommends electrodes of MIL type 120S-1 as applicable to HY-100 steel in either submerged arc (SAW) or shielded arc (GMA) processes. Chemical and mechanical properties for this and other electrode materials discussed are listed in tables A-5 and A-6. This specification requires only that fluxes used in SAW be a neutral granular material such that, in conjunction with the electrode, achieves the mechanical properties listed in Table A-6.

Parameters for the submerged arc process appear more clearly defined in MIL-E-22749 as revised by Amendment 11. This specification shows electrode type MIL-MI88 (Tables A-5 and A-6) used in conjunction with flux material MIL-MI will achieve a yield strength of 88,000 psi (min.). Recommended current voltage and travel rate for test samples are also given and listed in Tables A-7 and A-8. Similar information for the shielded arc process is available in MIL-E-19322A, as revised by Amendment 4 dated November 16, 1965. This specification assumes an electrode material of similar alloy to those listed in Table A-5. Though this document is the forerunner of MIL-E-23765/2A, the information gives an idea of the type of values necessary to achieve a joint possessing the required properties.

TABLE A-5

CHEMICAL COMPOSITION OF DEPOSITED WELD METAL

	MIL-120S-1 Percent	MIL-MI88 with MIL-MI (flux) Percent
Carbon	.10	.06
Manganese	1.40 - 1.80	1.00 - 1.50
Phosphorous	.01	.01
Sulfur	.01	.01
Silicon	.25 - .60	.50
Nickel	2.00 - 2.80	1.40 - 1.90
Chromium	.60	.10 - .30
Molybdenum	.30 - .65	.20 - .40
Copper	--	.10 - .30
Vanadium	.03	.05
Titanium	.10	.10
Zirconium	.10	.10
Aluminum	.10	.10
Iron	Remainder	Remainder

TABLE A-5

MECHANICAL PROPERTIES FOR AS-WELDED CONDITION

Mil-Type	Process	Tensile Properties: Ultimate psi	Tensile Properties: Yield psi .2% offset	Elongation min. % in 1.4" or 2"	Transverse Sidebend	Impact-Toughness: Charpy V-Notch: Energy ft./lbs. min.avg.	Impact-Toughness: Charpy V-Notch: Temp. °F	Impact-Toughness: Dynamic Tear: Energy ft./lbs. min.	Impact-Toughness: Dynamic Tear: Temp. °F	Explosion Bulge	Guided Bend
120S-1	Shielded & Sub-merged ARC	--	105,000 to 122,000	14	Note A	50	-60	450[B]	0	Comply with NAVSHIPS 0900-005-5000	--
MIL & MI Flux	Submerged ARC	110,000 max.	85,000 min.	20	--	70 55	-60 30	--	--	--	--
120S-1 Stress Relieved	--	Note C	Note C	Note C	--	Note C	10	--	--	--	Note D

Note A - Transverse side bend specimens shall be tested as specified in MIL-STD-418. The specimens after bending shall have no cracks greater than 1/8 inch in any direction on a convex surface.

Note B - Requirement for 5/8 inch dynamic tear test shall be in accordance with MIL-STD-1601.

Note C - The required mechanical properties after stress relief of high tensile strength weld metal shall be as specified. The electrode types shall be tested using d.c.r.p. (D.C. Reverse Polarity) for SAW & GMA & d.c.s.p. (D.C. Straight Polarity) for GTA.

Note D - Guided bend test specimens shall be tested as specified in MIL-STD-418. The specimens after bending shall have no cracks greater than 1/8 inch in any direction on a convex surface.

This electrode is described by the following chemical composition (from MIL-E-19822A).

	Percent
Carbon	0.08 max
Manganese	1.15 - 1.55
Phosphorus	0.025 max.
Sulfur	0.025 max.
Silicon	0.35 - 0.65
Nickel	1.15 - 1.55
Molybdenum	0.30 - 0.60
Vanadium	0.10 - 0.20

TABLE A-7

WELDING MACHINE SETTING (GROOVE WELDS)

Type of Electrode and Flux	Diameter Inch	Amperes	Volts	Travel Speed Inches/Minute
MIL-MI88[a] and	1/16	350-400	33-38	16
MIL-MI	3/32	500-550	33-35	32-34
Note b	.035	---	---	---
	.045	140-240	16-22	---
	1/16	275-375	26-30	---
	3/32	As recommended by Manufacturer		

Note a - MIL-MI88 is used with direct current reverse polarity
Note b - Assumes direct current straight polarity

TABLE A-8

FLUX PARTICLE SIZE REQUIREMENT

Type	% Retained on #12 Sieve (a) (Max.)	% Passing Through #140 Sieve (a) (Max.)
MIL-MI	6.5	2.0

Note a - U.S. Standard Series

Edges of the weld joint must be thoroughly wire brushed or sandblasted prior to welding. The weld region including the area within approximately one foot on either side is preheated to a temperature of 250°F to 350°F. These temperatures are maintained through the entire cross sectional thickness of the wall. When multi-pass welding is required, preening of layers is prohibited. Interpass temperatures are not allowed to exceed 300°F. Mechanisms to handle and manipulate the pressure hull to achieve the required weld rates are necessary. Also, a "chill block" metal base plate is required to assure penetration of the weld across the entire pressure hull wall thickness. The welds will be inspected radiographically and must meet the requirements of NAVSHIPS 0900-003-9000-Radiographic Standards for Production and Repair Welds.

It should be noted that samples of the welds performed by the pressure hull fabricator will be subject to properties performance tests. As a result, the process parameters and some electrode material compositions described herein are subject to change by the fabricator in order to achieve material properties (Ref. 14).

3.5 Assembly

Problems associated with assembly of the RTG will vary depending on the choice of closure mechanism. Welding requires preheat of the circumferential region about the joint until a temperature of 250°F to 350°F is achieved through the entire wall thickness. This heat input may require that external cooling be applied to the system to maintain temperatures near the hull/thermal fuse interface boundary below the melting point of the fusible insulation. Welding equipment that will perform the selected welding operation must be provided at the assembly site as well as positioning and manipulating equipment to achieve desired weld rates.

The closure must also be inspected for soundness. This presents a complex problem in that radiographic techniques require access to both sides of the welded seam. Available inspection processes are thus limited to Ultrasonics and Fluorescent Magnetic Particles (Ref. 15). The Fluorescent Magnetic Particle Method is used to sense changes in a material's magnetic field characteristic at flaws. It is applicable only to surface and near surface flaws, cannot detect microscopic flaws, and requires trained personnel to interpret formations. Also, flaw orientations with respect to that of the magnetic field determine the strength of the magnetic gradient. As a result, examination with magnetic fields of more than one direction (e.g. logitudinal and transverse) is desirable. Due to

these limitations, Magnetic Particle Inspection is best applied to pressure hulls that have an external cladding to detect flaws in the bond between the materials (Ref. 11).

Ultrasonic techniques can be used to detect microscopic flaws through the entire depth of the hull. However, since the process is one of interpreting the reflecting patterns of an acoustic wave traveling in the material, interpretation of patterns is crucial. Flaws occuring near either the interior or exterior surface can be misinterpreted as normal reflection. Orientation of the flaw with respect to wave direction is also important. Longitudinal and shear waves are transmitted in a direction perpendicular to and then parallel with the region of interest.

A new field of nondestructive testing under examination is Acoustic Emission techniques. The principle here is that the frequency of a wave traveling through a vessel with a flaw will differ from a frequence in a flawless region. However, this technique is still in the developmental stage; and, as such, its full capabilities and extent of limitations are not yet determined.

In view of the above, ultrasonics is the recommended weld closure inspection technique.

This restricts the assembly site to one with welding equipment or requires installation of the necessary equipment at the assembly site. The welded closure will also require that qualified welders be a part of the personnel assembling the system.

It is unlikely that the system would be stress relieved after the final weld. Stress relieving would require raising the system to a hull temperature of $1025^{\circ}F \pm 25^{\circ}F$ (Ref. 16) for one hour per inch of wall thickness,thus, placing an extremely severe thermal load on the system. Experimental work with welded shells under external pressure has been done at Naval Ship Research and Development Center. Test results have been plotted that compare failure pressure of HY-80 welded Ring Stiffened Cylinders to unwelded cylinders (Ref. 13). This work demonstrates that design allowances can be made for residual stresses.

Sealing the system by a bolted closure allows more flexibility in assembly site selection. For the most part, equipment required to complete assembly (mechanisms for lifting the system and components, equipment to accomplish argon backfill,

etc.) is common to either closure choice; as are the personnel required to implement and supervise the task.

Table A-9 provides a comparison of the impact of both mechanisms on the assembly process; and, as such, examines tradeoff considerations.

An examination was made of the possible impact of thermal mis-match between the surfaces of the closure. As listed earlier, the Coefficient of Linear Expansion for HY-100 steel is 7.1 x 10^{-6} in/in/^{o}F for the temperature range of 80^{o}F-[illegible]. If we assume room temperature to be 80^{o}F and that the inside wall temperature of the portion of the pressure hull in contact with the heat source does not exceed 1000^{o}F, (a reasonable assumption of the extreme case based on results reported in Reference 17) the linear expansion will be less than 8 mils. Once the upper flange is in contact with the lower flange [illegible] difference will be continually decreasing as thermal equilibrium is established.

Obviously, this analysis was for an extreme [illegible] temperatures of 1000^{o}F will present problems for [illegible] crew, thus establishing the need for external cooling [illegible] in turn, reducing thermal expansion. However, even with [illegible] differential of 920^{o}F, the mismatch will only be .004" on each side of the matching surfaces. This should cause no problem in the assembly process. Damage to the O-ring [illegible] by thermal expansion is also unlikely; .004" movement [illegible] cule compared to the anticipated movement while [illegible] the flange faces. Thermal mismatch is not anticipated [illegible] a problem.

3.6 Handling

Handling the pressure hull, and [illegible] the [illegible] system is a problem due to several factors. The [illegible] is physically a large item to transport. It is also [illegible] (approximately 19,000 pounds). Except for protecting [illegible], expecially the closure flange, from damage to as great [illegible] extent as is practicable; no special protection ([illegible]) oxidation) is required.

3.7 Operational Characteristics

It is expected that a welded closure achieved [illegible] parameters previously discussed will provide a 100 [illegible] joint for the life of the system (10 years). HY-100 [illegible] properties are not expected to degrade due to aging [illegible]. Corrosion effects, discussed previously, are well defined.

TABLE A-9

CLOSURE IMPACT ON ASSEMBLY PROCESS

Item	Equipment Required Unique to Closure Method		Advantage-Remark
	Weld	Bolt	
Closure Process Details	-Welding machine -Inert gas supply (shielded arc only) -Manipulators (rotating platform or rollers)	-Tools and process to torque bolts to proper stress	Bolt-Simple process & fewer equipment requirements
Pre Assembly Treatment	-Induction heaters or torches for pre-heat	-None at site (Flanged hull should be previously leak-tested by suitable environment simulations	Bolt-No treatment required
Post Assembly Treatment	--	--	No advantage for either method
Inspection	-Ultrasonic test of closure	--	Weld-Acceptable inspection technique minimizes chance of closure failure. No such process available to test bolt joint.

Increasing dimensions to allow for expected corrosion rates should eliminate this problem. Additional methods of corrosion protection are available, such as the use of sacrificial anodes. However, anode material selection is important (heat from the reaction with a Magnesium anode may crack the hull (Ref. 18).) Aluminum is a candidate that could meet the 10-year lifetime requirement. Anti-corrosion paint is another possible means of protection. It is possible that stress corrosion may occur in the weld region due to material changes (formation of martensitic grains) and residual stresses. However, the weld criteria previously discussed are designed to minimize these detrimental effects (Ref. 18). As a result, stress corrosion is not expected to occur on the RTG. These residual stresses also require dimensional design allowances. However, as previously described, data exists as to the required extent of such allowances.

A pressure hull with a bolted closure can be stress relieved and water quenched, if necessary, to completely eliminate residual stresses. Other corrosion effects can be minimized as discussed.

The mechanism for crevice corrosion attack is the deterioration by galvanic action of surfaces requiring a passive oxide film in an oxygen deficient environment. Since HY-100 steel does not depend on a passive film for corrosion resistance, it is not subject to crevice corrosion (Ref. 18).

One mechanism that could be responsible for joint degradation is O-ring extrusion. This phenomena is caused by pressure exerted on the ring in the gap clearance between flange faces that inelastically deforms (or extrudes) the ring into the gap clearance. The ring functions properly when it seals the gap clearance without being extruded.

O-ring extrusion may be prevented by a combination of minimized gap clearance and appropriate O-ring hardness (usually 70° Shore A Durometer minimum)(Ref. 19). Thin, back-up rings of much harder material can be fitted into the groove as shown (Figure A.4) to close the gap and provide clearance for the O-ring.

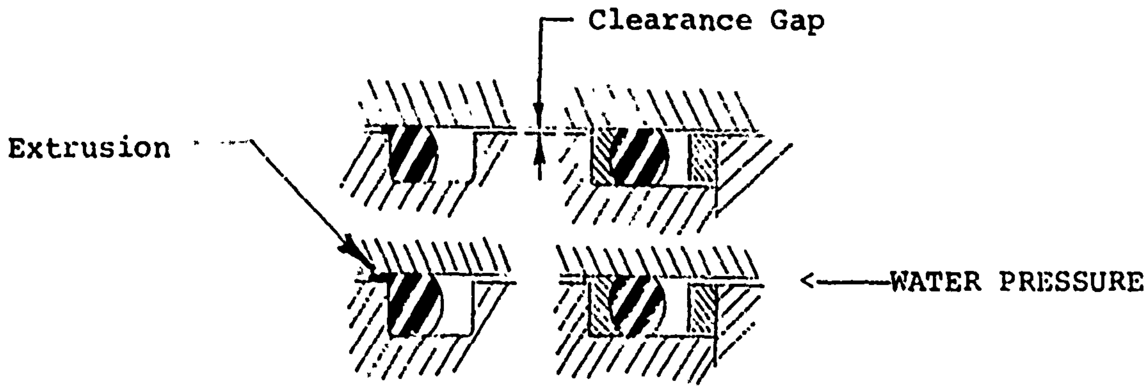


Figure A.4

4.0 RECOMMENDATION

Having discussed the considerations pertinent to either closure type it is apparent that either is technologically possible for the RTG application. Comparative advantages and disadvantages exist for either method.

Welding clearly offers greater reliability, though it places restrictions on the assembly site selection with the requirement of welding equipment. Welding also complicates the assembly process causing the addition of welders to accomplish the task. (It is assumed that the assembly site will not be the pressure hull fabricator's premises.)

Bolting provides for a simpler assembly operation, places fewer restrictions on the assembly site, and does not require welding personnel as part of the assembly crew. However, machining the flange with the precision required will complicate the fabrication of the pressure hull. This method also requires pressure testing the hull.

Secondary considerations involve system accessibility. Once the vessel is sealed by welding a component failure will abort the mission with a new or significantly reworked hull required. Bolting allows non-destructive accessibility.

In view of the preceding, the bolted closure is the recommended closure. Dominant considerations in making this recommendation are:

1. Restrictions placed by welding on site selection; especially if a site in proximity to a Navy port is required.

2. Capital investment of welding (and related) equipment.

3. Inaccessibility to interior of a welded system.

5.0 POSSIBLE ALTERNATE CLOSURE METHOD

The following suggestions are presented in an effort to examine the complete scope of the closure problem and available solutions.

From the preceding it is apparent that, though welding offers reliability advantages, bolting offers repeated system access as well as fewer complications and more flexibility during assembly.

The pressure vessel closure serves a dual purpose. It provides structural soundness and a seal that separates the system environment from the external environment. Perhaps these functions can be performed better by a separate mechanism for each, rather than by a single closure technique.

Such a closure might be configured as the bolted joint of Figure A.3. However, in place of the 12 bolt holes and bolts, a circumferential seal weld could be provided at the flange interface. For that case, the flange will bear the structural load, and the weld will provide the seal.

Another method that will accomplish this requires redesigning the bottom end of the pressure hull into a threaded, flat plate that will screw into the walls of the vessel. A seal weld bead can be applied. To provide adequate thickness to survive the bending stresses that would be experienced, the plate could be forged.

Either of these methods will require weld equipment at the assembly site. However, they will provide the reliability of a welded joint with accessibility possible by grinding off the weld bead. The welding required is not as laborious as for the structural weld of Figure A.3. Little rework is required for re-assembly. This concept should be reviewed in-depth.

Vacuum chamber closure joint design philosophy should also be reviewed to determine applicability to the pressure hull closure joint mechanical criteria.

5.0 REFERENCES

1. NSRDC "Preliminary Designs and Cost Estimates of Pressure Hulls for the Containment of a Portable Nuclear Electric Power Plant," F. Schwartz, May, 1973.

2. MIL-E-22749 (SHIPS)(and Amendment 11) "Military Specification, Electrodes (Bare) and Fluxes (Granular), Submerged Arc Welding, High Yield Low-Allow Steels," February, 1974.

3. ASME Boiler and Pressure Vessel Code, Section III, 1971, Section III Addenda, 1972; Section VIII, 1971.

4. Personal Communication with M. Alton, Armco Steel Corp., Washington, D. C., September 3, 1974.

5. Personal Communication with H. Joyce, U.S. Steel Corp., Pittsburgh, Pennsylvania, September 3, 1974.

6. Armco "Design and Application Data, Armco HY-80, HY-100, High Strength Notch-Tough Alloy Steel (MIL-S-16216G)," June, 1968.

7. USS "Ultra-Service Steels HY-80, HY-100" (MIL-S-16216G) June, 1970.

8. Personal Communication with R. Niederberger, NSRDC, November 1, 1974.

9. DMIC Report 245, "The Corrosion of Metals in Marine Environments," F. Fink, W. Boyd, May, 1970.

10. Personal Communication with L. Megow, Vice President, Hahn & Clay, Houston, Texas, October 31, 1974.

11. Personal Communication with B. Masell, Manager of Manufacturing, Babcock and Wilcox, Barberton, Ohio, November 1, 1974.

12. Personal Communication with H. Middlestat, President, Middlestat Machine Company, Baltimore, Maryland, October 21, 1974.

13. DTMB Report 1985, "Potential Hull Structures for Rescue and Search Vehicles of the Deep Submergence Systems Project," M. Krenzke, K. Horn, J. Proffitt, March, 1965.

REFERENCES (continued)

14. Personal Communication with Mr. R. Smith, Armco Corp., Houston, Texas, October 30, 1974.

15. NSRDC Report 1-15, "Non-Destructive Testing for Pressure Vessels," E. Petrisko, March, 1970.

16. MIL-E-23765/2A (SHIPS), "Military Specification, Electrodes and Rods-Welding, Bare, Solid, Low Alloy Steel," May, 1973.

17. ORNL-TM-3806 "Thermal Test of the Heat Block-Shield for the Isotope Kilowatt Program," M. Lackey,March, 1973.

18. Personal Communication with T. Dawson, NAVFAC, November 1, 1974.

19. "Parker O-Ring Handbook," June, 1957.

20. DTMB Report 1732, "An Experimental Investigation of Closures and Penetrations for Pressure Vessels of Composite Construction," T. Kiernan and M, Krenzke, February, 1964.

21. NCEL Technical Note N-1304 "Technical Investigation Supporting a 2KW(e) RTG Final Design," J. McCartney et al, August, 1973.

22. AAEC-TM-52, "Ultrasonic Testing of Closures for Rocket Heat 66 MM L1A2", J. Cole, May, 1973.

23. NASA-CR-102929 "Fastener Load Analysis Method," F. Rollins,Jr. August, 1970.

24. "Mechanical Engineering," Vol. 96/No. 9, September, 1974.

25. "Standard Handbook for Mechanical Engineers," Seventh Edition, T Baumeister and L. Marks, McGraw-Hill, 1958.

26. MIL-S-16216H (SHIPS), "Military Specification, Steel Plate, Alloy, Structural, High Yield Strength (HY-80 and HY-100)," March, 1972.

27. MIL-S-23008B (SHIPS), "Military Specification, Steel Castings, Alloy, High Yield Strength (HY-80 and HY-100)," September, 1964.

REFERENCES (continued)

28. MIL-E-22200F "Military Specification, Electrodes, Welding, Covered; General Specification For," October, 1973.

29. MIL-E-19822A (SHIPS)(And Amendment 4) "Military Specification, Electrodes, Welding, Bare, High Yield Steel," November, 1965.

30. "Nickel-Chromium-Molybdenum Steel Plate for Pressure Vessels," Lukens Steel Company, R. Sterne, Jr., L. Keay, October, 1974.

APPENDIX B

SAFETY AND COST BENEFIT COMPARISON

OF SAE 1010 STEEL VERSUS NICKEL ALLOY-201

HEAT BLOCK-SHIELD

1.0 INTRODUCTION

The following presents a safety and cost benefit comparison of a nickel versus a low-carbon steel heat block-shield for the subject power unit.

The heat block-shield specifications for this task are as follows: (Section 3.0)

Diameter	
Fin root, in.	35.5
Fin tip, in.	40.5
Height, in.	60.0
Holes for heat pipes	
Number	12
Diameter, in.	1.008
Length, in.	55.0
Holes for fuel capsules	
Number	7
Diameter, in.	4.153
Length, in.	50.25
Heat block-shield assembly shipping weight without fuel capsules, lb.	16,500
Normal surface operating temperature, ^{o}F.	1,150
Normal centerline operating temperature, ^{o}F	1,360
Accident surface temperature, ^{o}F	1,690
Accident centerline temperature, ^{o}F	2,175 (transient) 2,070 (steady state)

The above data are based on SAE1010 material for the heat block-shield. Nickel has been suggested as an alternative material, and a thermal analysis was performed (Ref.1). The nickel material utilized in the analysis was identified recently as "A" nickel (Ref. 2). "A" nickel is produced commercially as Nickel-200 (Inconel trademark). The nickel alloy for this comparison, however, is the low carbon Nickel-200 version which

is designated Nickel-201 (to be designated Ni-201 throughout this comparison). Ni-201 is preferred to Nickel 200 for applications involving exposure to temperatures above 600°F (Ref. 3). For this comparison, the accident surface and centerline temperature for Ni-201 are 1690°F and 1887°F, respectively.

2.0 COMPARISON OR PROPERTIES OF SAE 1010 STEEL AND NICKEL ALLOY NICKEL-201

2.1 Physical Description

A summary of the basic material physical properties, including density, specific heat, Curie temperature. modulus of elasticity, melting temperature and phase change temperature for Ni-201 and SAE1010 are given in Table B-1 (Ref.3 and 4 respectively). These physical properties are almost equal for both materials with two exceptions. First, the density of Ni-201 is 13 percent greater than SAE1010, and this would cause a 2145 pound increase in the weight of the heat block-shield of equal size. Second, and more important, SAE1010 goes through solid phase changes, and consequently, crystal structure changes. Upon heating above 1652°F (e.g. in the accident mode) there is a negative 1.6 volume percent change and an instantaneous step decrease in linear dimensions. The crystal structure change could cause stresses on the fuel capsules and heat pipes or change the heat transfer characteristics if a convection gap is utilized between the heat block-shield and the heat pipes and fuel capsules.

2.2 Chemical Properties

The chemical analyses for SAE1010 and Ni-201 are given in Table B-2 (Ref. 3 and 4, respectively). The alloys are almost pure iron and nickel, respectively. Since the heat block-shield is surrounded by fusible aluminum alloy insulation, it is of interest to note the solid solubility of aluminum in the two candidate materials. The solid solubilities of aluminum in iron and nickel at the accident surface temperature of 1690°F are 34 and 5 weight percent, respectively. The SAE1010 heat shield-block, therefore, would be more susceptible to diffusion of the aluminum into the heat shield-block.

2.3 Thermal Properties

The thermal properties presented herein include linear coefficients of expansion (Table B-3), thermal conductivity (Table B-4) and emissivity (Table B-5).

TABLE B-1

COMPARISON OF PHYSICAL PROPERTIES OF SAE1010 & Ni-201
(Ref. 3,4)

PROPERTY	SAE1010	Ni-201
Density, lb./in.^{3}	0.284	0.321
Specific Heat, Btu/lb./$^\circ$F (70°F)	0.115	0.109
Curie Temperature, $^\circ$F	1414.000	680.000
Modulus of Elasticity (Tension) 10^6 psi	29.800	30.000
Melting temperature, $^\circ$F	2720.000	2651.000
Temperature for Phase Changes from		
Ferrite + Pearlite ——>Ferrite + Austenite	1333°F *	---
Ferrite + Austenite ——> Austenite	1652°F **	---

* Essentially all ferrite at T <1333°F, and hence it has a body-centered cubic (bcc) structure.

** It has a face-centered cubic (fcc) structure.

TABLE B-2

CHEMICAL COMPOSITION OF SAE1010 & Ni-201
(Ref. 3,4)

ELEMENT	SAE1010	Ni-201
Fe	Remainder	0.40 max.
Ni (plus Co)	--	99.00 min.
Cu	--	0.25 max.
Mn	0.30-0.60	0.35 max.
C	0.08-0.13	0.02 max.
Si	--	0.35 max
S	0.05 max	0.01 max
P	0.04 max.	--

TABLE B-3

COMPARISON OF MEAN LINEAR EXPANSION OF SAE1010 & Ni-201

SAE1010		Ni-201*	
Temperature Range, ^{o}F	Value, in./in./$^{o}F \times 10^{-6}$	Temperature Range, ^{o}F	Value, in./in./$^{o}F \times 10^{-6}$
32-212	6.78	70-200	7.4
32-392	7.22	70-400	7.7
32-572	7.50	70-600	8.0
32-752	7.56	70-800	8.3
32-932	7.89	70-1000	8.5
32-1112	8.11	70-1200	8.7
32-1292	8.33	70-1400	8.9
32-1652	9.10	70-1600	9.1
1652	14.10	70-1800	9.3
1652-2000	14.50	70-2000	9.5

*Values for Ni-200 in annealed condition, but mean linear expansion for Ni-201 for 70-200^{o}F is 7.4 in./in./$^{o}F \times 10^{-6}$

TABLE B-4

COMPARISON OF THERMAL CONDUCTIVITY FOR SAE1010 AND Ni-201
(Ref. 3,4)

SAE1010		Ni-201	
Temperature Range, °F	Thermal Conductivity Btu/in./ft.^{2}/hr./°F	Temperature Range, °F	Thermal Conductivity Btu/in./ft.^{2}/hr./°F
212	400	70-200	512
392	368	70-400	460
572	342	70-600	408
752	316	70-800	392
932	284	70-1000	410
1112	255	70-1200	428
1292	229	70-1400	445
1472	197	70-1600	463
1832	191	70-1800	480
2192	206	70-2000	-

TABLE B-5

COMPARISON OF EMISSIVITIES OF SAE1010 & Ni-201
(Ref. 10)

	Emissivity, percent			
	SAE1010		Ni-201	
Temperature, °F	Oxidized	Polished	Oxidized	Polished
540	50	15	50	6
1040	57	28	58	9
1290	60	37	64	12
1540	63	37	70	14
2190	--	34	82	22

2.3.1 Linear coefficient of expansion

The linear coefficients of expansion of Ni 201 and SAE1010 are given in Table B-3 (Ref. 3 and 4 respectively). The SAE1010 data are for temperatures at and above 1652°F, (Ref.7). There is a step change in the linear coefficient of expansion at this temperature. The higher temperature face-centered cubic (fcc) structure causes about a 50 percent increase in the linear coefficient of expansion. The linear coefficient of expansion for SAE1010 for temperatures above 1652°F is also greater by 50 percent than that for the candidate fuel capsule material Hastelloy C-276 (Ref. 6). At comparable temperatures, the linear expansion coefficient for SAE1010, however, is less than that for stainless 316 the heat pipe material (Ref. 7). Thus, both SAE1010 and Ni-201 are satisfactory for the heat pipe interface while SAE1010 could be unsatisfactory for the fuel capsule interface in the accident mode.

2.3.2 Conductivity

The thermal conductivities of Ni-201 and SAE1010 versus temperatures are given in Table B-4 (Ref. 3 and 4 respectively). The thermal conductivity of nickel is about twice that of SAE1010. The Ni-201 alloy from this aspect is much more attractive, because at the accident mode temperature iron may not be used due to excessive fuel cladding temperature (Ref. 1).

The heat block-shield would probably be produced from a casting, and the physical properties would have directional (i.e. anisotropic) variation. Since SAE1010 and Ni-201 are very low alloy materials, attainment of isotropic physical properties is approached by hot forging operations. The properties quoted above are the isotropic values for the two materials. Service at the normal temperature of 1360°F, however, exceeds the recrystallization temperatures for both SAE1010 and Ni-201 (i.e. 1000 and 1100°F, respectively) Ref. 8. After recrystall0-zation, face-centered metals often exhibit a change from randomly oriented grains to grains with preferred orientation. If this occurred in the Ni-201 and SAE1010 which are both fcc at temperatures near and above the normal operating temperature, the directional thermal conductivity change would have to be accounted for in the design. In the case of Ni-201, directional properties were not observed in one test where the material fully recrystallized (Ref. 9).

TABLE B-6

COMPARISON OF SEAWATER CORROSION OF SAE1010 AND Ni-201

Alloy	Exposure Day	Exposure Depth, ft.	Corrosion Rate, mpy	Max. Pit Depth, Mils	Crevice Corrosion Depth, Mils	Corrosion Type*
1010	398	5	8.2	24	0	U, P
1010	366	5	8.0	--	--	G
1010	402	2370	1.2	--	--	U
1010	402	2370	1.1	--	--	G
1010	403	6780	1.5	--	--	U
1010	403	6780	2.3	--	--	G
1010	588	5	8.9	23	15	C, P
Ni-201	366	5	3.6	50 (PR)	50 (PR)	C, P
Ni-201	402	2370	0.6	50 (PR)	50 (PR)	C, P
Ni-201	403	6780	0.6	50 (PR)	50 (PR)	C, P

* U - Uniform
P - Pitting
G - General
C - Crevice
PR - Perforated

2.3.3 Emissivity

The emissivities for oxidized and polished SAE1010 and pure nickel versus temperature are presented in Table B-5 (Ref. 10). Pure nickel data were selected, because Ni-201 is almost pure. The emissivities increase for both materials in the oxidized condition. The effect of temperature (i.e. from 540° to 2190°F) is not greater for either material in either direction. The emissivities are about half for those reported in the thermal comparison analysis in Ref. 1.

2.4 Corrosion

The seawater corrosion of SAE1010 and Ni-201 is presented in Table B 6 from data of Ref. 11. As expected, Ni-201 is preferrable, because nickel appears lower on the electromotive series (i.e. it is cathodic compared to SAE1010), and nickel and its alloys are excellent for corrosion. Ni-201 also performs better than SAE1010 in high temperature salt solutions and dry and wet hydrochloric acid. Exact data for high temperature (about 1000°F) exposure to wet salt solutions, such as might occur for a pressure hull failure, are not available. However, for comparison, a corrosion rate of 1200 mils per year (mpy) would occur at 1250°F for Ni-201 and at 450°F for carbon steel (Ref. 12). Although both might be inadequate, Ni-201 is preferable from both general and hot corrosion characteristics.

In the event of a pressure hull failure, there could also be galvanic corrosion between the heat block-shield and the 316 stainless steel heat pipes, the plugs over the fuel capsule holes and the HY-100 pressure vessel. Ni-201 would be cathodic with reference to most of these materials except Hastelloy C-276. Ni-201 is slightly higher on the galvanic serice than Hastelloy C-276. On the other hand, SAE1010 would be anodic with reference to all these materials. In addition, in the neighborhood of welds (e.g., the plugs or the support structure for the heat block-shield) intergranular corrosion would be possible with the SAE1010 steel.

2.5 Oxidation

The oxidation rates for SAE1010 and Ni-201 are 4.8×10^{-7} and 2.9×10^{-10} gm cm^{-2} sec^{-1}, respectively, (Ref. 13). Since the pressure vessel is back-filled with argon, oxidation is only a concern during the fueling of the heat block-shield. Although oxidation should not be a problem, Ni-201, from the rates above, is preferable.

2.6 Strength at Operating Temperature

The mechanical properties at room and elevated temperatures for SAE1010 and Ni-201 are presented in Table B-7 (Ref. 14 and 3, respectively). The mechanical properties at room temperature are comparable for both materials. Ni-201 data at just below the operating temperature (i.e. data at 1150°F compared to 1360°F show a fifty percent reduction in strength but a large increase in ductility. High temperature data for SAE1010 were not obtained, but similar trends would be expected.

As mentioned in the thermal conductivity discussion, (Section 2.3.2) it has been observed that the isotropic properties obtained by forging of the casting can become directional (i.e. a preferred orientation) at temperatures in excess of the recrystallization temperature. As also mentioned in that section, however, there are some results to indicate that directional properties after recrystallization were not observed in Ni-201. The possible problem of a preferred orientation, however, should be verified for the final selected material.

2.7 Thermal Shock

Thermal shock results are not available for either material. The fuel capsules are subjected to a 1400°F to 32°F instantaneous immersion and held for a 10 minute shock test criteria (Section 3.0). For nominal conditions, it is not expected that either material would present a problem. However, if the heat block-shield is cooled from temperatures after loss of coolant (e.g., 1652°F), the crystal structure change in the SAE1010 which creates a 1.6 volume percent change could cause severe stresses at the heat pipes and fuel capsules. Since Ni-201 does not have this problem, it is preferable.

2.8 Fabricability

2.8.1 Machinability

Some sources (Ref.8) rate the machinability of Ni-201 to be the same as for SAE1010. A SAE1010 heat block-shield has been successfully machine (Ref. 10). It is indicated that Ni-201 can be machined at commercial rates provided that the practices outlined in Ref. 18 are followed. This material tends to flow under pressure of the tool cutting edge and form long, stringy chips. To avoid a built-up edge, tools should be ground with very high positive rake angles (e.g., 40° to 45°). High-speed steel or cast alloy tools should be used (Ref.3). The drilling of the relatively small, very long holes for the heat pipes and fuel capsules could be a problem

TABLE B-7

COMPARISON OF MECHANICAL PROPERTIES OF SAE1010 & Ni-201

Property	SAE1010	Ni-201*
Tensile Strength, Ksi	47	50-70
RT 1150°F	--	24.6
0.2% Offset Yield Strength, Ksi	26	12-35
RT 1150°F	--	10.7
Elongation in 2 in., %	28	60-35
RT 1150°F	--	73

*Values for hot-rolled plate

with Ni-201. Since chip removal and work hardening at the face of the tool are problems in apparently ductile face-centered metals (e.g. copper) machining of the Ni-201 could result in an increase in manufacturing cost as compared to an SAE1010 version.

2.8.2 Weldability

Both SAE1010 and Ni-201 can be welded easily by a variety of processes. However, oxyacetylene welding is not recommended for use on Ni-201. Inert gas welds are preferable for both materials.

2.9 Availability

Reference 16 indicated that a large forged cylinder of SAE 1010 is not a standard item, and a special request would be required. In addition, the minimum weight order is between 25 and 50 tons, while the present need is about 8 tons. No estimate of delivery time would be made without a formal request.

The situation for Ni-201 is similar. For a final cylindrical block of about 40 inch diameter by 60 inch long, the Huntington Products Division would be required to go to an outside vendor for the forging of the ingot. Huntington is somewhat anxious about providing a final product which is produced by another vendor. The quote on delivery, depending on their mill schedules, is 5 to 6 months (Ref. 17).

2.10 Cost

2.10.1 Direct

The costs per pound of SAE1010 and Ni-201 are $0.26 and $3.08, respectively (Ref. 16 and 17). If only one heat block-shield were required, however, the cost for SAE1010 could be about 6 times higher than indicated. The costs based on one heat block-shield would be about $13K - $26K and $57K for SAE1010 and Ni-201 ingots, respectively. Final machining costs would also probably be higher for Ni-201. The increased cost differential for the Ni-201, however, is probably small compared to the overall program cost.

2.10.2 Indirect

There are similar research and development costs associated with both materials (e.g., thermal shock tests for the SAE1010 and possible oriented physical properties determinations of both materials.)

3.0 SUMMARY

A comparison of the various properties is given in Table B-8 for SAE1010 and Ni-201. Ni-201 has preferrable physical properties (e.g. thermal conductivity, lack of phase change, corrosion and oxidation resistance). SAE1010 is only preferable from the point of view of ingot and machining costs, but the cost increase for Ni-201 is not felt to be substantial from improved physical property considerations and overall program costs. Both materials, however, require a fairly long lead time request to the vendors because of the ingot size and low alloy content (i.e. especially SAE1010). It is recommended, therefore, that Ni-201 be selected as the heat block-shield material instead of the present SAE1010.

TABLE B-8

COMPARISON OF PROPERTIES OF SAE1010 & Ni-201

DESIGN CONSIDERATION	Alloy Performance: SAE1010 Preferable	SAE1010 Adequate	SAE1010 Inadequate	Ni-201 Preferable	Ni-201 Adequate	Ni-201 Unsatis-factory	REMARKS
Density/Weight	x	x			x		Ni-201 represents a 2145 lb. increase for the same geometry, also better radiation shielding.
Phase Change (Effect on Linear Expan-sion)		x		x	x		In the accident mode SAE1010 has a phase change would cause a volume change and a step increase in the thermal expansion. Also, SAE1010 may have a problem from thermal shock after high temperature exposure.
Chemistry		x		x	x		Ni-201 has better corrosion and oxidation resistance.
Thermal Conductivity		x		x	x		Thermal conductivity of Ni-201 is twice that of SAE1010, and this result could be used to reduce heat block-shield centerline temperatures. There is a possible preferred orientation problem in Ni-201, due to recrystallization.
Emissivities		x		x	x		No clear advantages of one material or the other.
Corrosion a - Seawater			?	x	x		Less than 1 mpy for Ni-201.
b - Hot			?	x		?	Nickel in Ni-201 should provide some protection for hot corrosion which could occur after pressure vessel failure.

TABLE B 8 (continued)

COMPARISON OF PROPERTIES OF SAE1010 & Ni-201

DESIGN CONSIDERATION	SAE1010 Preferable	SAE1010 Adequate	SAE1010 Inadequate	Ni-201 Preferable	Ni-201 Adequate	Ni-201 Unsatisfactory	REMARKS
Oxidation		?		x	x		Since oxidation should only occur during fueling neither material should be damaged significantly.
Strength at Operating Temperatures		x			x		No clear advantages for either material. There is a possible preferred orientation problem after recrystallization.
Thermal Shock			?	x	x		Due to change in crystal structure SAE1010 could have a problem. Both must be tested.
Fabricability Machinability	x	x			x		Long deep holes for heat pipes and fuel capsules may require special machining care for Ni-201.
Weldability		x			x		No clear advantage for either material
Availability		?			?		Both materials would be special requirements for vendors. Ni-201 - no minimum, availability 5 - 6 months. SAE1010 - 25-50 ton minimum, availability - est. 1 - 2 months.

TABLE B-8 (continued)

COMPARISON OF PROPERTIES OF SAE1010 & Ni-201

Alloy Performance

DESIGN CONSIDERATION	SAE1010 Preferable	SAE1010 Adequate	SAE1010 Inadequate	Ni-201 Preferable	Ni-201 Adequate	Ni-201 Unsatis-factory	REMARKS
Cost: Direct	x	x			x		Cost for ingot and machining are substantially less for SAE1010, but not prohibitive for either material.
Indirect		x			x		No apparent advantage for either material. Both require thermal shock tests and Ni-201 requires physical property evaluation after recrystallization.
OVERALL RATING		x		x	x		

4.0 REFERENCES

1. Samuels, G., "Comparison of Nickel & Iron Heat Block-Shield," ORNL TM 3213, January, 1971.

2. Samuels, G., ORNL to DFH private communication, Dec., 1974.

3. Anon., "Nickel Alloys," 15M2-72T-15, Huntington Alloy Products Division, Huntington, W.Va., 1972.

4. Lyman, T., "Metals Handbook," ASM, Metals Park, Ohio, 1948.

5. Van Vlack, L.H., "Elements of Materials Science," Addison-Wesley, Reading, Mass., 1964.

6. Anon., "Hastelloy Alloy C-276," F-30 356D, Stellite Div., Cabot Corporation, Kokomo, Indiana, 1973.

7. Anon., "Aerospace Structural Metals Handbook," - Vol. I - Ferrous Alloys, ASD-TDR-63-741, DDC, AD420981, March, 1963.

8. Guy, A.G., "Elements of Physical Metallurgy," Addison-Wesley, Reading, Mass., 1967.

9. Burford, R.A., INCO to JM private communications, Dec., 1974.

10. Goldsmith, A., Waterman, T.E. and Hirschhorn, H.J., "Thermophysical Properties of Solid Materials" - Vol. I - Elements, WADC Technical Report 58-476, AD960500, Wright Air Development Division, Ohio, August, 1960.

11. Reinhart, F.M. and Jenkins, J.F., "Corrosion of Materials in Surface Seawater after 12 and 18 months of Exposure," Technical Note N-1213, Naval Civil Engineering Laboratory, Port Hueneme, California, January, 1972.

12. Anon., "Resistance to Corrosion," 25M(11-70) S-37, Huntington Alloy Products Division, Huntington, W.Va., 1970.

13. Wright, J.G., "Oxidation of Iron-, Nickel-, and Cobalt-Base Alloys," MCIC 72-07, Battelle-Columbus, Ohio, 1961.

14. Lyman, T., Metals Handbook," 8th Ed. - Vol. I - Properties and Selection of Metals, ASM, Metals Park, Ohio, 1961.

4.0 REFERENCES (continued)

15. Lackey, M.E., "Thermal Test of the Heat Block-Shield for the Isotope Kilowatt Program," ORNL-TM-3806, March, 1973.

16. Boslego, J., Bethlehem Steel Corporation to DFH, private communication, December, 1974.

17. Burford, R.A., INCO, to DFH private communication, Dec., 1974.

18. Boslego, J., Bethlehem Steel Corporation to DFH, private communication, December, 1974.

19. Burford, R.A., INCO, to DFH private communication, December, 1974.

APPENDIX C

SAFETY AND COST BENEFIT COMPARISON OF HASTELLOY C-276 VERSUS INCONEL-625 FUEL CAPSULE MATERIAL

1.0 INTRODUCTION

A safety and cost benefit comparison of a Hastelloy C-276 versus an Inconel-625 fuel capsule based on corrosion, heat transfer, fuel-metal compatability, and strength at operating temperature is performed on the following pages. Also, a maximum capsule temperature for each of these materials is recommended.

The fuel and fuel capsule specifications from Section 3.1 are as follows:

Design Life: 10 years
Fuel: Sr_2TiO_4
Fuel Half Life: 28.75 years
Allowable Capsule Corrosion Rate: 10^{-4} in/yr (uniform; no pitting)
Maximum Pressure: 15,000 psig
Thermal Shock: 1400°F to 32°F instantaneous immersion, held for 10 minutes
Maximum Capsule Operating Temperature: 1360°F (test data)
Maximum Capsule Emergency Temperature: 2175°F (<1 hr.transient) (test data)
Maximum Capsule Steady State Temperature after Heat Pipe Failure: 2070°F (>1 hr-long term) (test data)
Capsule Geometry: 40 in. long x 4.100 in. O.D. x 3.450 in. I.D. cylinder with welded caps on ends.

2.0 COMPARISON OF PROPERTIES OF HASTELLOY C-276 AND INCONEL-625

2.1 Chemistry

The vendor chemical analyses for Hastelloy C-276 (Ref.1) and Inconel-625 (Ref.2) alloys are given in Table C-1. The major constituents of the alloys (e.g. Ni, Cr, Mo, Co, and Fe) are in the same range for the two alloys. The slightly higher chromium content in Inconel-625 is favorable from the standpoint of oxidation (Ref.3) and hot corrosion resistance (Ref.4). These points will be discussed later in more detail.

2.2 Corrosion

Both Hastelloy C-276 and Inconel-625 are very cathodic. Both are cited as highly resistant to marine environments (Ref.5). Deep ocean data on Inconel-625 sheet at 2370 feet depth for 402 days show 0.1 mpy uniform corrosion rates in seawater and mud and no measurable crevice corrosion (Ref.6).

TABLE C-1

VENDOR CHEMICAL ANALYSES FOR
HASTELLOY C-276 & INCONEL-625 *
(Ref. 2,3)

	Hastelloy C-276	Inconel-625
Ni	Balance	Balance
Co	2.5	1.0
Cr	14.1-16.5	20.0-23.0
Mo	15.0-17.0	8.0-10.0
W	3.0- 4.5	--
Fe	4.0- 7.0	5.0
Si	0.05	0.50
Mn	1.00	0.50
C	0.02	0.10
V	0.35	--
P	0.03	0.015
S	0.03	0.015
Cb+Ta	--	3.15- 4.15
Al	--	0.40
Ti	--	0.40

*Values without ranges are maximum values

Similar data are not available for Hastelloy C-276, but the chemically similar Hastelloy C gives identical results compared to Inconel-625. Both alloys, therefore, meet the fuel capsule corrosion rate criterion of 10^{-4} ipy. Additional supporting data for Hastelloy C-276 are given in Ref. 7, while additional data for Inconel-625 are given in References 8 and 9.

Hastelloy C-276 and Inconel-625 are both highly resistant to all classes of salts (e.g. acid chlorides such as NH_3Cl, ZnCl, CuCl) at moderate temperatures 200-400°F (Ref. 7 and 9, respectively). Hastelloy C-276, for example, with less than 0.02 percent carbon is completely resistant to hot seawater (550°F) (Ref.5). High temperature exposure to salt water, however, is deleterious to both alloys. Results for tests run with JP4 fuel with 5 ppm NaCl/water at 1650°F are given in Table C-2 (Ref.4). Inconel-625 is somewhat better than Hastelloy C-276 for the high temperature salt water condition probably due to its higher chromium content. Haynes-188, a cobalt alloy with still higher chromium yields more favorable results as shown in Table C-2. Additional data for Inconel-625 show a 50 percent reduction in ultimate strength and a change in elongation from about 40 percent to 2 percent for a combined air and seawater environment at 1600°F (Ref.10).

The corrosion of Inconel-625 in pure high temperature steam is more favorable than in a salt environment. The corrosion metal loss is 0.1 mils per three years and 0.7 mils for 20 years at steam temperatures of 1050°F and 1150°F, respectively (Ref.11). Additional data (Ref. 12-15) for the affect of steam on Inconel-625 are similar. No similar data were found for Hastelloy C-276.

2.3 Thermal

The melting point, thermal conductivity, specific heat and thermal expansion of Hastelloy C-276 and Inconel-625 are given in Table C-3 (Ref. 1 and 2, respectively). The properties are slightly more favorable for Hastelloy C-276 for the proposed use.

2.4 Fuel-Metal Compatibility

Data pertaining to the fuel-metal compatibilities of Hastelloy C-276 and Inconel-625 with Sr_2TiO_4 are of very limited availability for the conditions specified. There are results, however, for Hastelloy C-276 with inert SrO at 1100°C (2012°F) for 200 hours. These data indicate that low silicon and carbon contents are not advantageous from the standpoint of reducing SrO attack of the Hastelloy C-276.

TABLE C-2

EFFECT OF HIGH TEMPERATURE (T=1650°F) NaCl WATER ON HASTELLOY C-276 & HAYNES 625*
(Ref.5)

Alloy	Time,Hr.	Total Mils Affected/Side
Haynes 625	200	4.0
Haynes 625	1000	12.0
Hastelloy C-276	200	8.2
Haynes 188	200	2.0
Haynes 188	1000	4.0

*Haynes 625 is Inconel-625 made under Inconel license to Stellite Division, Cabot Corporation

TABLE C-3

MELTING POINT, THERMAL CONDUCTIVITY, SPECIFIC HEAT, & THERMAL EXPANSION FOR HASTELLOY C-276 & INCONEL-625
(Ref. 2,3)

Alloy	Melting Temp. (°F)	Thermal Conductivity (BTU-in/ft²-hr-°F)		Specific Heat (BTU/lb.-°F)		Mean Coefficient of Thermal Expansion (Microinches/in-°F)	
Hastelloy C-276	2415-2500	1000°F	132		0.102*	75-1000°F	7.4
		1200°F	145			75-1200°F	7.8
		1400°F	159			75-1400°F	8.3
		1600°F	173			75-1600°F	8.8
		1800°F	185			75-1700°F	8.8
		2000°F	195				
Inconel-625	2350-2460	1000°F	121	1000°F	0.128*	70-1000°F	7.8
		1200°F	132	1200°F	0.135	70-1200°F	8.2
		1400°F	144	1400°F	0.141	70-1400°F	8.5
		1600°F	158	1600°F	0.148	70-1600°F	8.8
		1800°F	175	1800°F	0.154	70-1700°F	9.0
				2000°F	0.160		

*Calculated values

(Ref. 16 and 17). From these reports it is also interesting to note that the attack by SrO depends on the processing of the SrO; i.e. whether SrO (K_2CO_3) or SrO (NH_4CO_3) exists. Since Hastelloy C is chemically similar to Hastelloy C-276 with the exception of allowable C and Si content, it is also noted that for Sr_2TiO_4 with Hastelloy C at 900°C and 1100°C for 5000 hours the depth of interaction is only 7 mils. It is also noted that the SNAP 7A Hastelloy C fuel capsules (6 years at 932°F) showed no interaction (Ref. 18). There are no similar data for Inconel-625. Data with active strontium should be generated for both materials.

A compilation of melting point, thermal conductivity, specific heat, and thermal expansion data for Sr_2TiO_4 from reference 19 are given in Table C-4. Comparison of the Sr_2TiO_4 data from this Table C-4 with the Hastelloy C-276 and Inconel-625 data of Table C-3 show a good match of properties. The thermal coefficient of expansion of Sr_2TiO_4, for example, is less than that for either alloy.

2.5 Oxidation Behavior at Elevated Temperatures

The air oxidation behavior of Hastelloy C-276 and Inconel-625 is presented in Table C-5. Inconel-625 appears to have lower oxidation rates. This result is attributed to the higher chromium content (Ref.3). The oxidation behavior of both alloys at the shipping temperature of 1020°F is not reported, but the data in Table C-5 suggest that oxidation should not be a problem.

2.6 Strength at Operating Temperatures

Fuel capsules produced for testing in support of the Isotope Kilowatt Program were fabricated from 4½ inch diameter Hastelloy C-276 rod (Ref.22). The available mechanical properties of Hastelloy C-276, however, are not for rod. Available plate properties are presented herein. The mechanical properties at the operating and heat pipe failure temperatures are presented in Table C-6. The mechanical properties for Hastelloy C-276 and Inconel-625 are comparable. Although the mechanical properties at the operating temperatures are adequate compared to the design pressure values of about 15 Ksi, the recommended temperature for both alloys is about 1000°F (Ref. 21 and 23) due to the aging problem associated with both alloys. In fact, the Hastelloy fabrication literature recommends that Hastelloy alloys should not be aged at 1100 to 1800°F for prolonged periods of time, because aging causes carbide precipitation in the grain boundaries which leads to a loss of ductility and greater susceptibility to corrosive attack (Ref. 24). The elongation after aging for 100 hours at 1650°F decreases from 55 to 22 percent (Ref. 25). Inconel-625

TABLE C-4

MELTING POINT, THERMAL CONDUCTIVITY, SPECIFIC HEAT & THERMAL EXPANSION OF Sr_2TiO_4

(Ref. 20)

a. Melting Point: 3344-3416°F

b. Thermal Conductivity (BTU-in/ft^2-hr-°F)

T, °F	Value
1112	21.80
1472	20.90
1832	20.00
2192	19.45
2532	18.87

c. Specific Heat (BTU/lb-°F):

0.134@RT (Calculated Value)

d. Mean Linear Thermal Expansion (Microinches/in-°F):

T, °F	Value
1112	6.17
1292	6.17
1472	6.22
1652	6.28
1832	6.28
2012	6.33

TABLE C-5

OXIDATION BEHAVIOR OF HASTELLOY C-276 & INCONEL-625

Alloy	T, °F	Oxidation Rate (Mils/100 hour) Continuous	Interim Heat
Hastelloy C-276*	1800	9.5	9.7
	1900	19.2	15.7
	2000	142	253
	2150	1.04/6 hours	--
Inconel-625	1800**	--	0.023
	2100***	2.3 - 2.8	14

* Ref. 21

** Ref. 3

*** Ref. 22

TABLE C-6

SUMMARY OF MECHANICAL PROPERTIES AT VARIOUS TEMPERATURES

Property	Hastelloy C-276* 1360°F	Hastelloy C-276* 2070°F+	Hastelloy C-276* 2175°F+	Inconel-625** 1360°F	Inconel-625** 2070°F	Inconel-625** 2175°F
Tensile Strength, Ksi	80	12	10	88	12	--
0.2% Yield Stress, Ksi	31	8	7	40	10	--
Elongation, %	60	52	48	88	128	--
Modulus of Elasticity, 10^6 psi	23.5	--	--	23.1	--	--

* 0.75 inch plate heat-treated at 2100°F and water quenched (Ref. 2)

** Hot rolled solution-treated rod (Ref. 3)

\+ 0.094 inch sheet heat-treated at 2100°F and water quenched (Ref.2)

behaves in the same manner, but the reduction in elongation is from 54 to 37 percent for an aging of 1600°F for 2000 hours (Ref. 2). Also, at 1400°F long term aging of Inconel-625 results in the onset of overaging (i.e. no further increase in the hardness occurs with time) (Ref. 26 and 27). Additional results for aging at 1500°F for 290 hours also show the ductility of Hastelloy C-276 to be substantially degraded, while for Inconel-625, only a moderate decrease in ductility was observed (Ref. 8). Also, Inconel-625 was found to show little or no loss in ductility at 1300°F (Ref. 8).

Impact strength data for Hastelloy C-276 were not found in the literature. On the other hand, extensive impact strength data for Inconel-625 for aging temperatures from 1000°F to 1400°F are available (Ref. 28 and 29). These data show that the room temperature impact strength decreases from 57.5 ft.-lbs to 2.4 ft.-lbs after heating at 1360°F for 4000 hours. There is a recovery in the ductility, however, in Inconel-625 after heating at a temperature of 2100°F (Ref. 8). We expect this same result for Hastelloy C-276. Room temperature impact tests, however, are required after aging at 1360°F in excess of 100 hours. Also, similar tests after aging at 2070°F in excess of 100 hours and at 2175°F for at least one-half hour are required.

Thermal shock resistance is an important criterion for the selection of the fuel capsule material. A Hastelloy C-276 fuel capsule has passed a thermal shock test of quenching from 800°C (1472°F) to 0.5°C (32.9°F)(Ref.22). Similar data for Inconel-625 are presently not available.

Although not an important criterion in the present design, the available creep characteristics of Hastelloy C-276 and Inconel-625 are presented in Table C-7. The creep behavior for both alloys is comparable. Data at the operating temperature after heat pipe failure are not available and would have to be generated for both alloys, if required.

2.7 Fabricability

Both Hastelloy C-276 and Inconel-625 are readily machinable and weldable (e.g. TIG and MIG processes) (Ref. 1,2,24,30, and 31). Hastelloy C-276, if welded by the submerged arc process, is affected deleteriously by fluxes containing carbon or silicon, and such fluxes should be avoided.

TABLE C-7

CREEP CHARACTERISTICS OF HASTELLOY C-276 & INCONEL-625

Alloy	Test Temp. °F	Stress, Ksi	Min. Creep Rate (%/hr.)	Rupture Life (hours)
Hastelloy C-276*	1200	44.0	0.0838	763.5
	1600	17.0	12.16	12.5
	1800	7.6	8.71	10.9
	1800	3.7	0.067	630.4
Inconel-625**	1300	50.0	0.0720	95.9
		45.0	0.0289	276.8
		35.0	0.0025	1470.6
		35.0	0.0074	960.8
	1800	1.0	0.00017	--
		5.0***	0.355	88.6
	2000	2.5***	0.3625	40.0

* 3/4 inch plate-heat treated at 2100°F-water quenched (Ref. 2)

** 5/8 inch rod-solution annealed (grade 2) (Ref.22)

*** Same as **, but 9/16 inch rod.

3.0 EFFECT OF OPERATIONAL PARAMETERS ON MATERIAL SELECTION

The operation of the RTG can be divided into two modes; namely, (1) normal operation and (2) failure mode. Materials considerations under normal operation include cost and availability, fabrication, assembly/disassembly, and fuel compatibility. Failure mode considerations include short term transportation and handling accidents, heat pipe failure, pressure vessel failure and, pressure vessel and heat block fracture.

3.1 Normal Mode

3.1.1 Cost and Availability

The cost of Hastelloy C-276 is $5.50 to $6.50 per pound, while the cost of Inconel-625 is $4.00 to $4.50 per pound (Ref. 21). Neither of these costs is considered prohibitive.

The availability of Hastelloy C-276 is 18-20 weeks, but stocked material could be available sooner (Ref. 32). Hastelloy C-276 is the second generation alloy of the series Hastelloy C, C-276 and C4. There is some thought that Hastelloy C and C-276 will be phased out in preference to Hastelloy C-4 (Ref. 33). The availability of Inconel-625 is 6 to 18 months (Ref. 21). For the present dimensional requirements of 4.100 in.O.D. with a 0.325 in. wall thickness tubing, Inconel-625 is not available (Ref. 34) (i.e. outside of present production runs at Huntington Alloy Products Division). Inconel-625 rod would have to be machined to the dimensions required.

3.1.2 Fabrication

The machinability of both Hastelloy C-276 and Inconel-625 is quite satisfactory and within the present state-of-the-art. Both alloys also have good weldability. It is recommended, however, that submerged-arc welding with fluxes which contain high carbon and silicon contents be avoided in welding of Hastelloy C-276.

3.1.3 Assembly/Disassembly

In the assembly process, there are several considerations on capsule material properties; namely, oxidation behavior, impact strength, relative thermal expansion between the fuel capsule and heat block, and thermal shock.

The oxidation behaviors of Hastelloy C-276 and Inconel-625 were presented in Section 2.5 and the oxidation behaviors are presented in Table C-5. Both alloys are quite satisfactory, but Inconel-625 with its higher chromium content is slightly

better. Long term implications on the effect of the oxide layer on fuel capsule heat transfer characteristics are unknown but believed to be minor. Heat transfer coatings would reduce oxidation substantially.

It is conceivable for a fuel capsule to be dropped into the heat block during the insertion procedure. Both alloys are susceptible to age hardening which is deleterious to the impact strength. Hastelloy C-276 at 1360°F will begin to age harden in about one-half hour (Ref.25). Thus, Hastelloy C-276 may be unsatisfactory for this criterion. Results of a 30-foot drop test (Ref. 20), however, indicated that Hastelloy C-276 performed satisfactorily except for a poorly designed weld joint. This test is suspect, however, because there is no indication of the amount of soak time at temperature. Inconel-625 is also known to harden and lose room temperature ductility due to aging at temperatures above 1200°F for long times. As pointed out in Section 2.6, the reduction in ductility due to aging is less in Inconel-625 than Hastelloy C-276.

It is desirable from the point of view of capsule insertion that the heat block thermal expansion coefficient be less than the fuel capsule materials. Both Hastelloy C-276 and Inconel-625 however, have a lower thermal expansion coefficient (e.g. 7.4 and 7.8 microinch/in.°F for 70-1000°F, respectively), compared to the heat block SAE1010 material (8.1 microinch/in.°F) (Ref.35). This unfavorable difference is relatively minor but probably would have to be accounted for in the design of the heat block.

The insertion of the fuel capsule into an ambient temperature block amounts to a thermal shock to the capsules. Hastelloy C-276 fuel capsules have passed a thermal shock test of quenching from 800°C (1472°F) to 1/2°C (32.9°F) (Ref.22). Quench data for Inconel-625 are not available.

3.1.4 Fuel-Metal Compatibility During Normal Operation

The fuel-metal compatibility during normal operation (1360°F) has not been determined for Hastelloy C-276 or Inconel-625. Hastelloy C-276 has been tested with non-radioactive SrO at 1100°C (2012°F) as discussed previously in Section 2.4 The performance of Hastelloy C in the SNAP-7A generators at 932°F and tests on Hastelloy C with non-radioactive Sr_2TiO_4 at 900°C (1652°F) and 1100°C (2012°F) indicated negligible fuel-metal interaction. There is, however, a reduction in the mechanical strength properties of about 50% and an elongation reduction from 30% to 11% (Ref. 16 and 17).

Similar data at 1360°F with radioactive Sr_2TiO_4 would have to be obtained (since the strontium decay products, Yttrium and Zirconium, may have some adverse effects) for both Hastelloy C-276 and Inconel-625.

The differential thermal expansion problem of the fuel capsule and heat block has already been mentioned from the insertion consideration. In addition, the heat block must be designed in such a manner so as not to overload the capsules. The creep strength of the fuel capsules at the operating temperature of 1360°F is probably adequate. Creep data for long times (i.e. >50,000 hr.)is not available for other alloys.

Finally, contact of the heat block and fuel capsules could cause a migration of carbon from the heat block into the capsules. In both alloys, the addition of small amounts of carbon would accelerate the age hardening behavior. No test data are available.

3.2 Failure Mode

3.2.1 Transportation and Handling

Dropping the fuel capsules, rupture of the fuel capsule transportation container, and fire represent the possible hazardous situations for the fuel capsule during transportation and handling. These situations represent short time conditions. The impact situation has been previously discussed (Section 3.1.3). Exposure of the fuel capsule to air or salt water/air leads to oxidation and corrosion. For short times, both Hastelloy C-276 and Inconel-625 have adequate oxidation and corrosion resistance (See Sections 2.5 and 2.2, respectively). As to whether such short duration exposure would have longer term effects remains to be determined. The effect of a fire (<1800°F in air) would be to increase the oxidation rate. Inconel-625 has a lower oxidation rate at 2000°F than Hastelloy C-276 (see Table C-5). Both alloys, nevertheless, are satisfactory.

3.2.2 Heat Pipe Failure

The transient capsule temperature is 2175°F (<1 hr.)and the steady state temperature is 2070°F after heat pipe failure. The implications of this failure are high temperature fuel-metal compatibility, fuel capsule-heat block interaction and thermal expansion and creep strain of the fuel capsule relative to the heat block. All these implications have been discussed previously. The need for testing of the fuel-metal compatibility at high temperatures in both materials is reiterated. Diffusion of carbon across the heat block-fuel capsule interface has also been mentioned, and the diffusion rate would certainly increase at the high temperatures associated with heat pipe failure.

Accomodation of the thermal expansion and creep strain of the fuel capsule has also been mentioned and again the magnitude would be increased at these higher temperatures.

3.2.3 Pressure Vessel Failure

The effects of pressure vessel failure would be thermal shock and compressive stresses. The latter will not cause a failure in the fuel capsules. A successful thermal shock test has been performed on Hastelloy C-276, but no test has been performed on Inconel-625. The requirement for a test on Inconel-625 has been presented previously (Section 2.6).

3.2.4 Heat Block Failure After Pressure Vessel Failure

This situation would cause sea water with up to 5 ml/l dissolved oxygen to come in contact with fuel capsules. In addition, a restrictive leak may allow the salt water to reach temperatures above 1000°F. Thus both general and hot seawater corrosion of the fuel capsules must be considered. Both alloys have acceptable low temperature seawater corrosion resistance (i.e. $<10^{-4}$ ipy). Hot seawater corrosion, however, is very deleterious to both alloys (See Section 2.2). Inconel-625 due to its higher chromium content, has a lower hot corrosion rate than Hastelloy C-276 (e.g. 4.0 mils/200 hrs. compared to 8.2 mil/200 hours, respectively). Based on linear extrapolation of these rates, Inconel-625 would last 2 years compared to 1 year for Hastelloy C-276. This indicates a potential safety problem and implies a design requirement that pressure vessel failure and subsequent heat block failure cannot be allowed. Actually, Inconel-625 is not recommended for hot corrosion at temperatures of 1000°F or greater (Ref. 28) and Haynes 188, a cobalt based alloy with high chromium content, is preferable to Hastelloy C-276 for hot corrosion (Ref.4). A better alternate Inconel alloy, both from aging and hot corrosion considerations, is Inconel-617 (Ref. 31 and 36).

4.0 SUMMARY

A comparison of the important properties is given in Table C-8 for Hastelloy C-276 and Inconel-625. Both alloys have almost equivalent properties. The judgment as to preference in almost all cases is based on very slight differences. The hot corrosion resistance and oxidation resistance of Inconel-625 are, however, enhanced by the higher chromium content of this alloy. Neither alloy, nevertheless, appears to be completely satisfactory for the high operating and failure temperatures especially for long times. The recommended commercial temperature limit for both alloys is less than 1000°F. In addition,

the research and development tests required to certify either alloy as delineated in Table C-9 are extensive. Due to the inadequacies and unknowns of both materials and the testing required, it might be of interest to consider either Haynes 188 instead of Hastelloy C-276 and Inconel-617 instead of Inconel-625. Further analysis of these alternatives is recommended before final selection of the fuel capsule material is made.

TABLE C-8

COMPARISON OF PROPERTIES OF HASTELLOY C-276 & INCONEL-625

Design Consideration	Desired Design Property	Alloy Performance: Hastelloy C-276 Preferable	Hastelloy C-276 Adequate	Hastelloy C-276 Unsatis-factory	Inconel -625 Preferable	Inconel -625 Adequate	Inconel -625 Unsatis-factory	Remarks
Corrosion A. General	10^{-4} ipy	x	x			x		Both have rates $<10^{-4}$ ipy. Hastelloy C-276 is listed as slightly more noble. Both are cathodic.
B. Salt Water 500°F			x		x	x		Inconel-625 has higher CR content.
C. Salt Water 1500°F				x	x		x	Both are inadequate at or above 1000°F, but Inconel-625 has higher Cr content and is therefore slightly better.
Fuel-Metal Compatibility	Compatible @ 1360°F (10yrs) 2070°F (>1hr) 2175°F (<1hr)	 x x x						No data available for either, but Hastelloy C-276 has shown good compatibility with SrO at high temperatures ([illegible]2012°F).
Aging Behavior	Impact Strength @ RT After Long Time @: 1360°F 2070°F (>1hr) 2175°F (<1hr)			 x x x			 x x x	No data available except 30' drop test on Hastelloy C-276 after heating to 14[illegible]2°F for undetermined length of time. Both alloys age harden, but degree seems less in Inconel-625. Both are suggested not to be operated about 1200°F for long times.

TABLE C-8 (continued)

COMPARISON OF PROPERTIES OF HAST. .OY C-276 & INCONEL-625

Design Consideration	Desired Design Property	Alloy Performance: Hastelloy C-276 Preferable	Hastelloy C-276 Adequate	Hastelloy C-276 Unsatis-factory	Inconel-625 Preferable	Inconel-625 Adequate	Inconel-625 Unsatis-factory	Remarks
Strength @ Operating Temperature	1360°F-14Ksi 2070°F-14Ksi 2175°F-14Ksi		x x		x x			Data not available.
Thermal Shock	Quench 1472°F to 32°F	x	x					Hastelloy C-276 has passed thermal shock test. No test has been performed on Inconel-625.
Oxidation Resistance	@ 1580°F		x		x	x		Inconel-625 is preferable because chromium content is higher.
Fabricability	Weldability Machinability	 x	x x		x 	x x		Hastelloy C-276 is susceptible to fluxes with carbon/silicon especially in submerged welding.
Availability	2nd half FY75	x	x			x		Hastelloy C-276 has an 8-16 wk delivery compared to 6 mo. for Inconel-625
Cost	Direct		x		x	x		Inconel-625 is $4-5/lb., Hastelloy C-276 is $5.5-6.5/lb.
	Indirect R&D	x		x			x	Hastelloy has one test (thermal shock) complete, but both require R&D.

TABLE C-9

TEST & DATA REQUIREMENTS OF HASTELLOY C-276 AND INCONEL-625 FOR APPLICATION AS FUEL CAPSULE MATERIALS

Test Required	Hastelloy C-276	Inconel-625
High temperature (>500°F) Seawater Corrosion Tests	x	x
Fuel Metal Compatibility Tests		
@ 1360°F	x	x
@ 2070°F	x	x
@ 2175°F	x	x
Impact Strength After Exposure to		
1360°F for 100hr	x	-
2070°F for 100hr	x	x
2175°F for <1hr	x	-
Oxidation Behavior		
@ 1580°F	x	x
@ >2000°F	x	x
Thermal Shock Tests (Quench 1472°F to 32°F)	-	x
Creep Tests		
@ 1360°F for $>10^4$hrs.	x	x
@ 2070°F for $>10^4$hrs.	x	x

5.0 REFERENCES

1. Anon., "Hastelloy Alloy C-276," F-30, 356D, Stellite Division, Cabot Corporation, Kokomo, Ind., 1973.

2. Anon., "Inconel Alloy 625," 20M 9-70 T-42, Huntington Alloy Products Division, Huntington, W.Va., 1970.

3. Wright, I.G., "Oxidation of Iron-, Nickel-, and Cobalt-Base Alloys," MCIC 72-07, Battelle-Columbus, Ohio, June, 1972.

4. Hodge - Stellite Division, Cabot Corporation Private Communication, 1974.

5. Fink, F.W. and Boyd, W.K., "The Corrosion of Metals in Marine Environments," Bayer & Co., Inc., Columbus, Ohio, 1970.

6. Reinhart, F.M., "Corrosion of Materials in Hydrospace," U.S. NCEL, TR 504, Port Hueneme, Calif., Dec., 1966.

7. Anon., "Corrosion Resistance of Hastelloy Alloys," F-30, 131-E, Stellite Division, Cabot Corporation, Kokomo, Ind., 1970.

8. Anon., "Spherical Capsule Technology Program - Heat Source Technical Report," HIT-370, Hittman Assoc., Inc., Columbia, Maryland, January, 1969.

9. Anon., "Resistance to Corrosion," 25M (11-70) S-37, Huntington Alloy Products Division, Huntington, W.Va., 1970.

10. Paton, N.E., Robertson, W.M. and Mansfeld, F., "Hight Temperature Behavior of Superalloys Exposed to Sodium Chloride: 1 Mechanical Properties," Met. Trans. 4, 397, 1973.

11. Vazaldo, G.P. and Pearl, W.T., "General Corrosion of Stainless Steels and Nickel Base Alloys Exposed Isothermally in Superheated Steam," Corr. 21, 355, 1965.

12. Hammond, J.P., "Steam Corrosion of Advanced Steam Generator Systems," ORNL 4470, p. 153.

13. Hammond, J.P., "General Corrosion at 595 and 650°C and Weldability," ORNL 4560, p. 275.

5.0 REFERENCES (cont'd.)

14. Van der Line and Van Tilborg, "Corrosion Behavior in Canning Materials," RCN 111, p. 61.

15. Gaul, G.G. and Pearl, W.T., "Corrosion with Heat Transfer," GEAP-4932, p. 6-1.

16. DiStefano, J.R. and McHenry, R.E., "Compatibility of Strontium Compounds with Superalloys at 900 and 1100°C," ORNL-4625, November, 1971.

17. DiStefano, J.R., "Compatibility of Strontium Compounds with Superalloys at 900 and 1100°C," Nucl. Tech. 17, 127, 1973.

18. Shor, R., Lafferty, R.H., Jr., and Baker, P.S., "Strontium-90 Heat Sources," ORNL-IIC-36, May, 1971.

19. Reinshaw, S.J. and Ketchen, E.E., "Strontium-90 Data Sheets," ORNL-4358, March, 1969.

20. Haff, K.W., "Isotope Kilowatt Program Fueled Capsule Design and Evaluation - A Safety Analysis," ORNL-TM-3230, May, 1974.

21. R. A. Burford, Huntington Alloys to D.F. Hasson RPM letter communication, 1974.

22. Bradley, N.C., "Isotope Kilowatt Program Fuel Capsule Testing," ORNL-TM-4350, October, 1973.

23. Tacket, J., Stellite-Cabot to DFH private communication, 1974.

24. Anon., "Fabrication of Hastelloy Alloys," F-30, 126G., Stellite Division, Cabot Corporation, Kokomo, Ind., 1974.

25. Anon., "Hastelloy Alloy C-4," F-30, 526A, Stellite Div., Cabot Corporation, Kokomo, Ind., 1974.

26. ---, "Inconel-625" GEAP, 4745, p. 4-3.

27. ---, "Inconel-625 and Inconel-718," GEAP 4751, p. 3-17.

28. R. Burford, Huntington Alloy Products, INCO to D.F. Hasson, letter communication including INCO Report, "Effects of Elevated Temperature Exposure on the Properties of Inconel Alloy 625", 1974.

5.0 REFERENCES (cont'd.)

29. Kimball, O.F. Pieren, W.R. and Roberts, D.I., "Effects of Elevated-Temperature Aging on the Mechanical Properties and Ductility of Ni-Cr-Mo-Cb Alloy 625," Gulf-GA-A12683, General Atomic Co., San Diego, Calif, Oct. 1, 1974.

30. Anon., "Machining," 20M 2-71 T-12, Huntington Alloys Products Div., INCO, Huntington, W.Va., 1971.

31. Anon., "Joining" 25 M 5-72, T-2, Huntington Alloy Products Div., INCO, Huntington, W.Va., 1972.

32. Healy-Stellite-Cabot to J. Moore, private communication, 1974.

33. R. Donnelly ORNL to DFH, private communication, 1974.

34. J. Burford, Huntington Alloys, Inco., to J. Moore, private communication, 1974.

35. Lyman, T., "Metals Handbook," p. 555, American Society for Metals, Metals Park, Ohio, 1948.

36. Anon., "Inconel Alloy 617," 20M 9-72 T-46, Huntington Products Div., Huntington, W.Va., 1972.

APPENDIX D

HEAT EFFECTS DURING TRANSPORTATION

1.0 Introduction

Transport of the heat block-shield with the thermal sources installed is assumed to be by open flat-bed vehicle. A thermal guard surrounds the block. The DOT/NRC criterion for thermal safety is that no point on or outside this guard should reach a temperature above 180°F. It is assumed that cooling of the block is by radiation and natural convection only. Forced convection due to vehicle motion is neglected since the vehicle is not always moving.

As an initial step in evaluating the temperature limits achievable on and outside the guard, a simplified analysis of the ORNL measurements (Ref.1) has been made. ORNL has made measurements on a prototype block, using electrical heaters to simulate the radioisotope thermal sources. With the cylinder axis vertical, and 34 kilowatts (116,000 BTU/Hr) input power, the heat block-shield surface temperature at equilibrium was 500°F at mid-height, dropping to 425-450°F at the ends. The purpose of this initial simple analysis was to evaluate the partition of the cooling between radiative and convective modes.

2.0 Radiative Cooling

To evaluate the radiative cooling, it was assumed the block radiated from the top and cylindrical side as a black body. Radiation from the bottom was omitted, since the block support would obstruct that path. The block was modeled as a cylinder, with a height of 60" and a diameter of 35.5" (the fin root diameter.) The assumption of black body radiation seemed valid in several accounts. The emissivity of rough steel plate, which seems reasonable for the block surface, is about 0.96 in the temperature region of interest. In addition, the fin structure forms rather deep cavity-like regions, which increases the similarity to an ideal black body. The depth is 2.5", the approximate width at the bottom is 2" and at the top is 2.3", making a fairly deep cavity. With the assumption of black-body radiation, an estimate of the radiative flux, f, can be made.

$$f = \sigma(T^4 - T_\infty^4)A$$

σ = Stefan-Boltzmann constant

$= .1714 \times 10^{-8}$ BTU HR^{-1} FT^{-2}

T = block (absolute) temperature (°R)

T_∞ = ambient (absolute) temperature (°R)

A = radiating area

$= 53.3$ ft^2

Summarizing:

$$f = 8.5 \times 10^{-5} \ (T^4 - T_\infty^4) \text{ BTU ft}^{-2} \text{ Hr}^{-1}$$

$$(T \text{ in } {}^\circ R)$$

An average block temperature of 470°F was assumed. The fluxes evaluated for 50°F and 100°F ambient temperatures are 62,000 and 59,000 BTU/Hr. respectively. This implies that 55,000 - 58,000 BTU/Hr. must be removed convectively.

3.0 Convective Cooling

To evaluate the convective cooling, it was assumed 58,000 BTU/Hr. must be dissipated. A calculation was made to determine whether the requisite surface temperature was consistent with the measured value. The procedures of Rohsenow and Choi (loc. cit.) were followed. The convective flow is parameterized in terms of the Prandtl number, Pr, the Grashof number, Gr, and the Nusselt Number, Nu, all dimensionless. (Values indicated are for air.)

$Pr = c\mu/k = 0.72$

c = specific heat = (7.3×10^{-5} BTU Ft^{-3} $^\circ F^{-3}$)

μ = absolute viscosity

k = thermal conductivity=(.017 BTU Ft^{-1} Hr^{-1} $^\circ F^{-1}$)

$Gr = g\beta \ (T-T_\infty) x^3/\nu^2$

g = gravitational acceleration = 32.2 ft. $sec.^{-2}$

β = thermal coefficient of volume expansion = (1/T for perfect gas)

T_w = wall temperature (°K)

T_∞ = ambient temperature

x = distance along wall (in.)

$\nu = \mu/\rho$, (ρ=density) ($\nu = .239 \times 10^{-3} ft.^2 sec.^{-1}$)

$Nu = hx/k$

h = heat transfer coefficient = $q/(T-T_\infty)$

q = specific heat flow at the surface

For the case at hand, the product, $Pr \cdot Gr$, is about 10^{10} and the relation, based on correlation with several experiments, is well approximated by:

$$Nu = 0.13\ (Pr \cdot Gr)^{1/3}$$

$$\frac{q}{T-T_\infty} \cdot \frac{x}{k} = 0.13\ (Pr)^{1/3} (g\beta (T-T_\infty) x^3/\nu^2)^{1/3}$$

$$q = Q/A$$

Q = power to be dissipated $\approx$(1.7 x 10^4watts)

A = area of wall.

$$T - T_\infty\ 4/3 = \frac{Qx}{A\ k(0.13)(Pr)^{1/3}(q\beta/\nu^2)^{1/3} x}$$

$$T_W - T_\infty = Z(0.13Ak)^{-1}(Pr\ g\beta/\nu^2)^{-1/3 \cdot 3/4}$$

In evaluating this expression, an appropriate average value for β should be employed. One choice is:

$$\beta = 1/Tav$$

$$T_{av} = \frac{1}{2}\ (Tw + T_\infty)$$

Another choice is:

$$\beta = \frac{1}{2}\ (\frac{1}{T_W} + \frac{1}{T_\infty}).$$

These lead to slightly different values but the differences are unimportant for the purposes at hand. The results are also somewhat dependent on the T value assumed for T_∞, the ambient temperature.

3.1 Solution 1 - Smooth Cylinder

The expression was first evaluated for a cylinder 60" long, 17.75" radius, i.e., the cylinder corresponding to the radius at the root of the fins. The calculated temperature for 58,000 BTU/Hr. dissipated ranged from 690-740°F, depending on the choice of parameters.

3.2 Solution 2 - Cylinder With Fins

Since the measured difference is in the region of 400-450°F, depending on the value taken for the (unknown) ambient laboratory temperature, this first evaluation was not adequate. The explanation is clear in the fact that the cooling from the fins was neglected. The fins substantially increase the value of A. It was clear that, with the actual fin configuration, the simple flow scheme here considered could not pertain to the entire fin structure, since the corners would significantly change the flow pattern. Including the fins fully, would however, give a bounds.

Since the temperature increment varies at $A^{-3/4}$, the ratio of increments for two areas, A_1 and A_2, is:

$$\frac{(T - T_\infty)_1}{(T - T_\infty)_2} = \left[\frac{A_2}{A_1}\right]^{3/4}$$

The ratio of the areas, the length being constant, is just the ratio of the perimeters. Without fins the perimeter, in inches, is $2\pi(17.75")$. With the 45 fins, each 2.5" deep, 0.5" thick, the perimeter is:

$$2\pi(17.75) + 45\ (5\ 0) = 2\pi(17.75) + 225$$

$$= 111.5 + 225$$

Thus,

$$(T-T_\infty)_{fins} = (T-T_\infty)_{no\ fins} \left[\frac{2\pi(17.75)}{2\pi(17.75 + 225}\right]^{3/4}$$

$$= 700^\circ F \left[1 + \frac{225}{2\pi(17.75)}\right]^{-3/4}$$

$$= 700^\circ F/2.87$$

$$\doteq 300^\circ F.$$

This result, is , as was expected, too low. The fact that the two results bracketed the measured value indicated the validity of the analysis and that a working picture of the cooling was available. A more detailed analysis to evaluate the shape effects in detail was not considered necessary. However, for later developments, an "effective" perimeter was derived by adjusting the area to give the correct temperature increment. This effective perimeter was around 18 ft. (compared to a cylinder only perimeter of 9.3 ft. and a cylinder plus fins perimeter of 28 ft.)

4.0 Thermal Hazard - Effect of Radiant Flux

With this understanding of the cooling mechanism, a background is available for the evaluation of problems in block transport, the answers to which cannot be obtained by mere extrapolation of the ORNL experimental results. Specifically, these are the questions of possible thermal radiation to neighboring structures, the temperature of the heatguard, the temperature of the heated air rising above the block, and the maximum temperature of the vehicle bed.

If an open mesh heatguard is assumed, the thermal radiation will impinge on the neighboring structures. The absorption and emission of radiation by the neighboring structures depends on the physical and optical properties of structures. Therefore, it was felt that a reasonable approach was to estimate the radiative flux as a function of distance. The block was again modeled as a cylinder. The flux was evaluated in a horizontal plane at mid-cylinder height, the region where it is highest.

Close to the block, the radiant flux field is well approximated by an infinite cylinder At a distance, R, from the block axis the flux, f, would be, assuming 58,000 BTU/hr. per 60" length,

$$f = \frac{58 \times 10^3}{2\pi R\ 60} \qquad \text{BTU/hr. in}^2 \quad \text{(R in inches)}$$

$$= 23.9R \qquad \text{BTU/hr. in}^2 \quad \text{(R in inches)}$$

This approximation is plotted in Fig. D.1 as the "cylindrical approximation."

The cylindrical approximation is clearly not valid at large distances. For large values of R, the flux ought to vary as R^{-2}, i.e., as a point source. Assuming a uniform temperature on the block (taken to have radius, a, and length, 2ℓ) and restricting the calculation to the mid-height plane, an integral for the flux through unit area, normal to the radius can be written

$$f = \frac{\sigma T^4}{\pi} \iint \frac{(R - a\cos\alpha)\quad(R\cos\alpha - a)}{(R^2 + a^2 - 2aR\cos\alpha + z^2)^2}\, dz\, a d\alpha$$

(α and z are cylindrical coordinates)

The energy to be radiated, q, is given by

$$Q = \sigma T^4 (2\pi a) \quad (2\ell) \quad = 58{,}000 \text{ BTU/HR.}$$

The range of integration is $1 > \cos\alpha > a/R$ and $-\ell < z < \ell$. An exact evaluation of this integral did not seem worthwhile but an approximate form was derived:

$$f = \frac{Q}{\pi^2 R^2} \left(1 - \frac{\ell^2}{6R^2}\right) \left(1 + \frac{25}{6}\ \frac{a^2}{R^2} + \frac{291}{40}\ \frac{a^4}{R^4}\right)$$

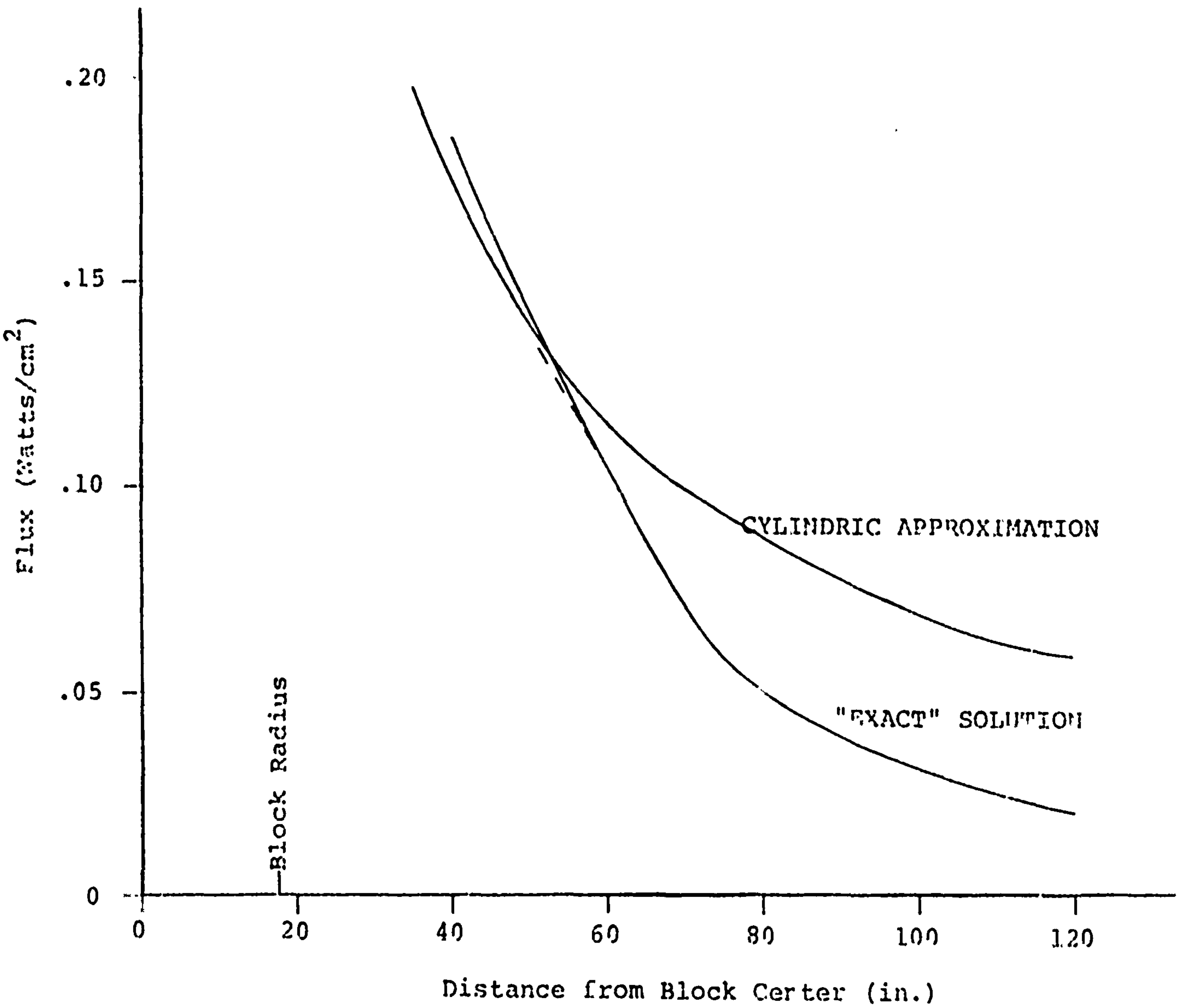


Fig. D.1 Plot of Radiant Flux from Heat Block Shield by Cylindrical and Exact Methods.

Clearly this solution is not valid close to the cylinder. The factor Q/π^2R^2 occurs instead of an isotropic point source value, $Q/4\pi R^2$, due to the dependence (of the black-body radiation intensity) on angle from the surface normal. The values of f are shown in Fig. 2.1 as the "exact" solution. The matching of the two solutions near 50" is quite good. An interpolation curve has been approximated.

The interpretation of the effect of this radiant heat flux on a neighboring surface is, as previously remarked, strongly dependent on the particular surface. To indicate the magnitude of the effect, the flux calculated has been applied to the problem of the mesh container temperature. It is assumed that the mesh guard is eight feet in diameter and ten feet high At 48" the calculated flux incident on the mesh is 463 BTU/HR. The methods of calculating the convective and radiative cooling are essentially the same as before. The relation between Nu and the product Pr·Gr is changed, as a different temperature range is involved. The new relation is

$$Nu = 0.56\ (Pr \cdot Gr)^{1/4}$$

The cooling of a wire of 0.1" thickness was calculated as characteristic of the mesh material. The result indicates a wire temperature $88^{o}F$ above ambient. Thus, the container does not appear to exceed safety tolerances unless the ambient temperatures approach $100^{o}F$. It should also be noted that the flux level used is the highest incident on the mesh, leading to an estimate for the largest temperature increase. This example also indicates that expected temperature rises in structures adjacent to the vehicle should not be excessive. At a distance of six feet from the center of the block, the flux is less than half the value at the guard location. Thus neighboring vehicles and structures would generally receive lower fluxes.

5.0 Air Temperature Rise Due to Convective Cooling

The next property to be evaluated concerned the heated air rising from the block, is the air providing convective cooling. The boundary layer thickness and average velocity were calculated following standard, experimentally based, relations (Ref. 3).

$$\delta = 3.93\ (Pr)^{-1/2}\ (0.952 + Pr)^{1/4} \left(\frac{g\beta(Tw-T\infty)}{\nu^2}\right)^{-1/4} x^{1/4}\ \text{(cm)}$$

$$u_{max} = 0.766\ \nu(0.952 + Pr)^{-1/2} \left(\frac{g\beta(Tw-T\infty)}{\nu^2}\right)^{1/2} x^{1/2}\ \text{(cm/sec)}$$

$$U_{av} = 9/16\ u_{max}$$

Using these values, together with the effective perimeter, the heat capacity of air and the assumed 17 kilowatt convective heat, the average air temperature rise was calculated. The values found were:

$$\delta = .55 \text{ in.}$$

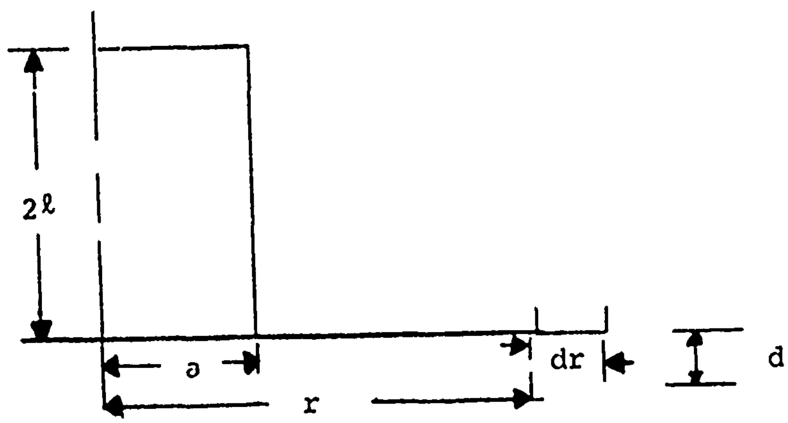
$$u_{max} = 68.9 \text{ in/sec.}$$

$$\tilde{T} = 310^{o}F$$

Clearly, this temperature rise is incompatible with the DOT/NRC safety criterion. A method to dilute this heated air is needed. A simple baffle system above the block could be introduced to deflect the heated columns radially and, mix it with unheated air and spread the area of flux over a larger part of the top of the container. The necessity of such a baffle system was part of the motivation in choosing the height of the mesh container as ten feet.

6.0 Heating of Vehicle Bed

The last question of thermal effects on transport concerns the heating of the vehicle bed. Treating the bed as a flat slab of thickness, d, with temperature depending only on the distance from the center of the contact between the block and the bed, an energy balance equation was written.



The energy conducted into a ring of radius r, width Δr is:

$$2\pi \; kd \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r}\right) \Delta r$$

The energy reradiated from this strip is:

$$2\pi r \varepsilon \sigma (T^4 - T_\infty{}^4) \Delta r$$

where ε is the surface emissivity, generally dependent on T. The energy absorbed by the surface from the block is

$$(2\pi r\Delta r\ \alpha\sigma\ T_\beta{}^4/\pi)\ \left(\tan^{-1}\sqrt{\frac{r+a}{r-a}}\right.$$

$$\tan^{-1}\sqrt{\left(\frac{r-a}{r+a}\right)\left(\frac{(r+a)^2+r\ell^2}{(r-a)^2+4\ell^2}\right)}$$

$$-\sqrt{1+8a^2\ell^2/\ (r^2-a^2+4\ell^2)^2}$$

where T_β is block temperature and α is the fraction of incident radiation absorbed. For the region $r \gtrsim 2a$ this is reasonably approximated by:

$$(2\pi r\Delta r\alpha\sigma T_\beta{}^4/\pi)\ \frac{4a\ell^2 r}{(r^2+a^2)\ (r^2+a^2+4\ell^2)}$$

For equilibrium the resultant energy equation is:

$$0 = \frac{dk}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) - \varepsilon\sigma(T^4-T_\infty{}^4) + (\alpha\sigma T_\beta{}^4/\pi)\frac{4a\ell^2 r}{(r^2+a^2)\ (r^2+a^2+4\ell^2)}$$

This highly non-linear equation is not amenable to exact analysis. It does, however, lend itself to some interpretation. For no conduction at a point, r, this means:

$$T^4 = T_\infty{}^4 + \frac{\alpha}{\varepsilon}\ \frac{T_\beta{}^4}{\pi}\ \frac{4a\ell^2 r}{(r^2+a^2)(r^2+a^2+4\ell^2)}$$

Evaluating this at the mesh edge, assuming $T_\infty = 50^\circ F$,

$T_\beta = 500^\circ F$, $\alpha=\varepsilon=1$ (black body), yields:

$$T = 127^\circ F$$

a reasonable temperature for our considerations. A rough approximation is:

$$T \simeq T_\beta\ \left(\frac{4a^2\ell}{\pi}\right)^{1/4}\ r^{-3/4}$$

This is useful primarily to estimate the relative magnitude of the terms. In particular, the ratio of conduction and reradiation is:

$$\frac{\frac{Kd}{r}\ \frac{\partial}{\partial r}\ \left(r\frac{\partial T}{\partial r}\right)}{\sigma T^4} \approx \frac{9/4\ dk}{\sigma T^3}$$

Taking 4 in. thick concrete, 36" out, and a temperature of $150^{\circ}F$, this ratio is about 12%. Thus the balance between the absorption of incident radiation and reradiation is the primary mechanism.

The approximate truck bed temperature at the edge of the mesh container is well within the reference safety criterion. The assumption has been that the bed is of low conductivity. A point which has not been covered is the temperature of the bottom side of the bed. The detailed evaluation of this depends too much on the details of support structure to allow much evaluation. It should be possible to keep it low providing the block rests on a sufficient insulating pad.

7.0 Conclusion

From the preceding it is apparent that a protective barrier must be provided around the source-shield assembly (SSA) for it to meet DOT/NRC regulations. The barrier must have minimum dimensions of 8 ft. in diameter and 10 ft. high. It must provide baffling to mix cold air with the hot air rising from the SSA, and must also provide insulation between the base of the SSA and the carrier bed.

A protective barrier including these features will allow shipment of the SSA without violation of the applicable DOT/NRC regulations.

REFERENCES

1. Lackey, M. E., "Thermal Test of the Heat Block-Shield for the Isotope Kilowatt Program," Oak Ridge National Laboratory, ORNL-TM-3806, March, 1973.

2. Rohsenow, W. H. and Choi, H.Y., "Heat, Mass and Momentum Transfer," Prentice Hall, Inc., Englewood Cliffs, New Jersey, 1961.

3. Eckert, E. R. G., "Introduction to the Transfer of Heat and Mass," McGraw-Hill Book Co., New York, 1950.

APPENDIX E

EARTHQUAKE ROCKING ANALYSIS

1.0 Introduction

The RTG is analyzed on a support base resting on the seabed foundation, but otherwise unrestrained. The support base is assumed to be the same as the width of the RTG as shown in Figure E-1.

2.0 Dynamic Analysis

It is assumed that an earthquake of one "g" (32 ft./sec^2) horizontal acceleration, having a frequency of one Hertz (cycle/sec) acts on the seabed foundation. This analysis is performed to see if the RTG will pass the critical tip-over angle (ϕ = o) before the reverse motion begins to restore it to the vertical.

For the position (x, y), velocity and acceleration of the center of gravity of the RTG in polar coordinates is:

$$x = \chi + r\cos\theta \tag{1}$$

$$\dot{x} = \dot{\chi} - r\sin\theta\,\dot{\theta} \tag{2}$$

$$\ddot{x} = \ddot{\chi} - r\cos\theta\,\dot{\theta}^2 - r\sin\theta\,\ddot{\theta} \tag{3}$$

$$y = r\sin\theta \tag{4}$$

$$\dot{y} = r\cos\theta\,\dot{\theta} \tag{5}$$

$$\ddot{y} = r\cos\theta\,\ddot{\theta} - r\sin\theta\,\dot{\theta}^2 \tag{6}$$

By Newton's Third Law, the force F along the force vector from the corner to the center of gravity is:

$$m\ddot{x} = F\cos\theta \tag{7}$$

$$m\ddot{y} = F\sin\theta - mg \tag{8}$$

where m is the RTG mass.

Eliminating $\ddot{x}$ and $\ddot{y}$ from 7 and 8

$$\cos\theta(r\cos\theta\,\ddot{\theta} - r\sin\theta\,\dot{\theta}^2) - \sin\theta(\ddot{\chi} - r\cos\theta\,\dot{\theta}^2 - r\sin\theta\,\ddot{\theta})$$

$$= -g\cos$$

$$r\ddot{\theta} = \ddot{\chi}\sin\theta - g\cos\theta$$

Let $\phi = \frac{\pi}{2} - \theta$ and treating ϕ as small gives the differential equation of the motion:

$$r\ddot{\phi} - g\phi = -\ddot{\chi} \tag{9}$$

The homogenous solution is

$$\phi_H = A\sin\sqrt{\frac{g}{r}}\,t + B\cos\sqrt{\frac{g}{r}}\,t \tag{10}$$

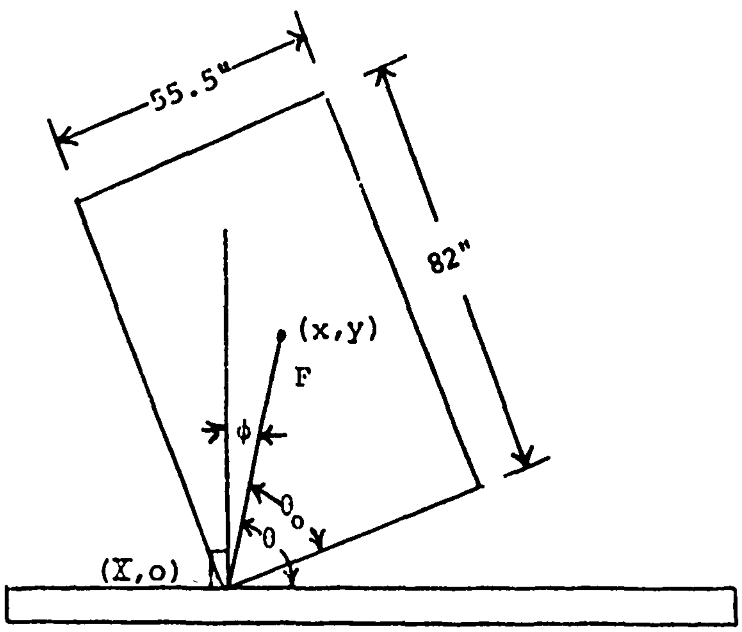


FIGURE E-1. RTG Being Rocked by Earthquake

and the inhomogenous solution is

$$\phi_I = C \sin \omega\ (t + t_o) \tag{11}$$

$$C = \frac{a}{\omega^2 r + g} \tag{12}$$

the boundary conditions are

$$\phi\ (0) = \phi_o \tag{13}$$

$$\dot{\phi}\ (0) = 0 \tag{14}$$

hence

$$B = \frac{-a}{\omega^2\ r + g} \sin \omega\ t_o \tag{15}$$

$$A = -\sqrt{\frac{r}{g}} \frac{a\omega}{(\omega^2 + g)} \cos \omega\ t_o \tag{16}$$

The final result is:

$$\phi(t)=\phi_o+\frac{a/g}{\omega^2 r/g+1}\left[\sin\omega(t+t_o)-\sqrt{\frac{r}{g}}\,\omega\cos\omega t_o\ \sin\sqrt{\frac{g}{r}}\,t-\sin\omega t_o\ \cos\sqrt{\frac{g}{r}}\,t\right] \tag{17}$$

Using the values $r = 125.1$ cm., $\omega=2\pi$, $a/g = 1$, ϕ is plotted in Figure E-2

It is noted that the closest approach to the critical angle $\phi = 0$ is 10.5^o and the RTG should not topple even with 1 g acceleration. However, the water drag has been omitted from the analysis because of the low velocities associated with the earthquake (2.7 mph peak). This will have a tendency to reduce ϕ. Furthermore, vertical acceleration has not been introduced. Its effect will be stabilizing or destabilizing depending upon the phasing between vertical and horizontal oscillations.

3.0 Conclusion

It is therefore concluded that a 1 g earthquake is approximately that required to topple the RTG from the seabed.

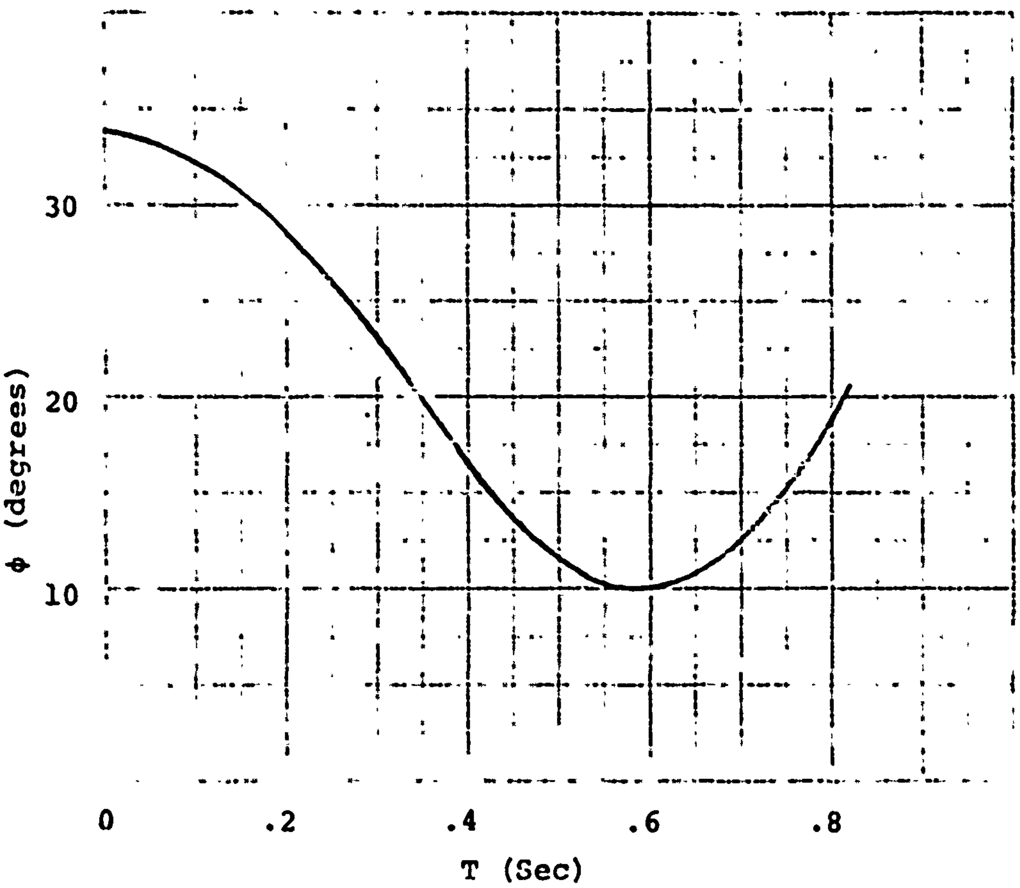


FIGURE E-2. Plot of Difference between the Force Vector Angle and the Vertical (ϕ) as a Function of Time.

APPENDIX F

APPLICABLE TRANSPORTATION SAFETY REGULATIONS

1.0 Introduction

The shipment of radioactive materials by commercial carrier in the U.S. is regulated by the Nuclear Regulatory Commission (NRC) (Ref. 3) and the Department of Transportation (DOT) (Ref. 4).

2.0 Requirements

Qualification as Special Form Material is required for the level of radioactivity required to produce 34 KW of heat. These criteria are presented in 49CFR 173.398 and 10 CFR 71 Appendices A and B. These criteria specify that the encapsulated fuel must show its integrity under the following conditions:

Stability: It must not melt, sublime or ignite at temperatures below 1475°F. Each source pellet, or the capsule material, must not dissolve or convert into dispersible form to the extent of more than 0.005 percent by weight, by immersion for 1 week in water at pH 6-8 and 68°F., and a maximum conductivity of 10 micromhos/centimeter, and by immersion in air at 86°F.

1. Free drop. A free drop through a distance of 30 feet to a flat essentially unyielding horizontal surface, striking the surface in such a position as to suffer maximum damage.

2. Percussion. Impact of the flat circular end of a one inch diameter steel rod weighing three pounds, dropped through a distance of 40 inches. The capsule or material shall be placed on a sheet of lead, of hardness number 3.5 to 4.5 on the Vickers scale, and not more than one inch thick, supported by a smooth, essentially unyielding surface.

3. Heating. Heating in air to a temperature of 1,475°F and remaining at that temperature for a period of 10 minutes.

4. Immersion. Immersion for 24 hours in water at room temperature. The water shall be at pH 6 - ph8 with a maximum conductivity of 10 micromhos/cm.

The "type B" container required for shipping the fuel capsules is subject to the following sequential cumulative tests:

1. Free Drop. A free drop through a distance of 30 feet onto a flat essentially unyielding horizontal target surface, striking the surface in a position for which maximum damage is expected.

2. Puncture. A free drop through a distance of 40 inches striking in a position for which maximum damage is expected, the top end of a vertical cylindrical mild steel bar mounted on an essentially unyielding horizontal surface, the bar shall be 6 inches in diameter, with the top horizontal and its edge rounded to a radius of not more than one-fourth inch, and of such a length as to cause maximum damage to the package, but not less than 8 inches long. The long axis of the bar shall be perpendicular to the unyielding horizontal surface.

3. Thermal. Exposure to a thermal test in which the heat input to the package is not less than that which would result from exposure of the whole package to a thermal radiation environment of 1,475°F for 30 minutes with an emissivity coefficient of 0.9 assuming the surfaces of the package have an absorption coefficient of 0.8. The package shall not be cooled artificially until 3 hours after the test period unless it can be shown that the temperature on the inside of the package has begun to fall in less than 3 hours.

4. Water immersion (fissile radioactive materials packages only). Immersion in water to the extent that all portions of the package to be tested are under at least 3 feet of water for a period of not less than 8 hours.

3.0 Qualification

It is not necessary to actually conduct the tests prescribed in this section if it can be clearly shown, through engineering evaluations or comparative data, that the material or item would be capable of performing satisfactorily under the prescribed test conditions.

4.0 Additional Requirements

In addition to these requirements, the Department of Transportation imposes the following requirements:

1. The outside of each package must incorporate a feature such as a seal, which is not readily breakable and which, while intact, will be evidence that the package has not been illicitly opened.

2. The smallest outside dimension of any package must be 4 inches or greater.

3. Radioactive materials must be packaged in packagings which have been designed to maintain shielding efficiency and leak tightness so that under conditions normally incident to transportation, there will be no release of radioactive material. If necessary, additional suitable inside packaging must be used. Each package must be capable of meeting the standards in section 173.398 (b) (see also section 173.24). Specification containers listed as authorized for radioactive materials shipments may be assumed to meet those standards, provided the packages do not exceed the gross weight limits prescribed for those containers in Part 178 of this chapter.

4. Internal bracing or cushioning, where used, must be adequate to assure that, under the conditions normally incident to transportation, the distance from the inner container or radioactive material to the outside wall of the package remains within the limits for which the package design was based, and the radiation dose rate external to the package does not exceed the transport index number shown on the label. Inner shield closures must be positively secured to prevent loss of the contents.

5. The heat generated within the package because of the radioactive materials present will not, at any time during transportation, affect the efficiency of the package under the conditions normally incident to transportation, and

6. The temperature of the accessible external surfaces of the package will not exceed 122°F in the shade when fully loaded, assuming still air at ambient temperature. If the package is transported in a transport vehicle consigned for the sole use of the consignor, the maximum accessible external surface temperature shall be 180°F.

Furthermore, shielding will be provided such that the following conditions are met:

1. 1,000 millirem per hour at 3 feet from the external surface of the package (closed transport vehicle only),

2. 200 millirem per hour at any point on the external surface of the car or vehicle (closed transport vehicle only).

5.0 Summary

It is because of these requirements that the heat sources will probably be shipped in the block-shield. This shield meets or exceeds all the previous requirements with the exception of the contact temperature limit of 180°F. In order to satisfy this requirement, the source-shield assembly should be encased in an expanded metal protector (steel for lower heat conductivity).

The mesh protector package will satisfy most of the requirements for type "A" packaging including the 49 CFR 173.398 drop test. This test requires that there be no loss of radioactive material if subjected to the 30 foot drop test oriented to product maximum damage. Under this test, the mesh screen would undoubtedly be seriously deformed. This would not compromise the shield integrity which is capable of sustaining the 30 foot drop test without loss of radioactive material.